Return to Sport after ACL Reconstruction and Other Knee Operations

Limiting the Risk of Reinjury and Maximizing Athletic Performance

Frank R. Noyes
Sue Barber-Westin
Editors

Springer

Return to Sport after ACL Reconstruction and Other Knee Operations

Frank R. Noyes • Sue Barber-Westin
Editors

Return to Sport after ACL Reconstruction and Other Knee Operations

Limiting the Risk of Reinjury and Maximizing Athletic Performance

Springer

Editors
Frank R. Noyes
Professor of Orthopaedic Surgery
Emeritus, University of Cincinnati
College of Medicine
Noyes Knee Institute
Cincinnati, OH
USA

Sue Barber-Westin
Noyes Knee Institute
Cincinnati, OH
USA

ISBN 978-3-030-22360-1 ISBN 978-3-030-22361-8 (eBook)
https://doi.org/10.1007/978-3-030-22361-8

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The numerous benefits of sports participation are well recognized, and as such, involvement in athletics has increased dramatically. The 2019 Physical Activity Council's Overview Report on United States athletic participation stated that approximately 218.5 million individuals aged 6 and over participated in some type of sports activity [1]. In 2018, the National Federation of State High School Associations reported an all-time record of nearly 8 million athletic participants, approximately 3.4 million girls and 4.6 million boys [2]. In 2018, over 480,000 athletes participated in collegiate sports [3].

Unfortunately, the negative effect of increased participation in sports in young athletes has been an upward surge in the rate of injury. For instance, recent investigations [4–6] estimated that in the United States, high school soccer knee-related injuries would occur in 259,587 girls and in 114,384 boys on a yearly basis, with ligament tears the most common diagnosis. Knee injuries are also among the most common of all injuries sustained in collegiate basketball [7]. Nearly a million anterior cruciate ligament (ACL) injuries occur each year worldwide, most of which are sustained by young athletes less than 25 years of age.

The issue of return to sport (RTS) after knee injuries, particularly ACL tears, has become a relatively recent topic of widespread research. Over a decade ago, a few reports appeared in the literature citing unacceptable reinjury rates in both the ACL-reconstructed and contralateral knee [8, 9]. These injury rates were much higher than those typically reported in registry studies (<5%) and sounded an alarm to the orthopedic community as a whole to seriously study reinjury rates as related to RTS [10–12]. We conducted a systematic review of studies published from 2001 to 2011 that determined factors used to allow RTS after ACL reconstruction and found that only 13% of 264 studies included objective criteria. All of this information highlighted the serious need to re-examine the rehabilitation of serious knee injuries and the necessity to include further quantification of restoration of normal indices before release to unrestricted athletic activities.

Our Medline searches conducted in 2019 reveal hundreds of articles that discuss wide variability in RTS rates after ACL reconstruction, lack of consensus regarding objective criteria that should be achieved before release to unrestricted activities, problems with psychological readiness and fear not usually addressed clinically, and high reinjury rates in young athletes. Issues regarding rehabilitation principles and practices, including advanced neuromuscular and motor retraining, have become critical topics for evidence-based research.

The question of what is causing the sometimes alarming rate of reinjuries (to either knee) upon RTS, even though patients appear to have normal or very good knee function restored, remains unanswered. Although we have made major advances in terms of ACL graft selection, positioning, tensioning, and fixation, the need to address associated instabilities in the knee joint, and decreasing postoperative complications, we have not yet achieved a standard of care in crucial rehabilitation factors that allow a safe RTS.

Collectively, these issues provided the impetus for the development of this textbook. We invited worldwide experts to participate and discuss their research findings in a manner that offers realistic and clinically feasible concepts for all medical personal involved in the care of athletes. While this textbook focuses many chapters on ACL injuries, other common knee injuries and operations are included, such as meniscus procedures, patellofemoral realignment, articular cartilage restoration procedures, total knee arthroplasty, and partial knee arthroplasty. Four chapters focus on examination and testing to determine knee function, neuromuscular indices, muscle strength, dynamic balance and stability, and neurocognitive factors.

An important point to highlight is the essential team approach by medical professionals that is required to successfully return the high school, collegiate, or professional athlete to competition. As discussed recently by Wang et al. [13], this team encompasses not only the orthopedic surgeon but also the physical therapist and athletic trainer who spend the majority of time with the athlete over the course of rehabilitation. The therapist and trainer are responsible for forming a relationship of trust with the patient immediately and must understand their goals, personality, potential problems with fear, and compliance. This textbook provides eight chapters dedicated to rehabilitation principles essential for the successful RTS.

There is still much work to be done to continue to advance our knowledge in this area. That being said, we hope the material in this textbook provides clinically feasible principles that medical professionals may implement immediately in their practice.

Cincinnati, OH, USA — Frank R. Noyes
Cincinnati, OH, USA — Sue Barber-Westin

References

1. The Physical Activity Countil. 2019 Physical activity council's overview report on U.S. participation. 2019. www.physicalactivitycouncil.com/pdfs/current.pdf. Accessed 27 Mar 2019.
2. National Federation of State High School Associations. Participation statistics. 2018. https://www.nfhs.org/ParticipationStatistics/ParticipationStatistics/. Accessed 27 Mar 2019.
3. National Collegiate Athletic Association. Estimated probability of competing in college athletics. 2018. http://www.ncaa.org/about/resources/research/estimated-probability-competing-college-athletics. Accessed 27 Mar 2019.

4. Clifton D, Onate J, Hertel J, Currie D, Knowles S, Pierpoint L, Wasserman E, Comstock R, Dompier T, Kerr Z. Descriptive epidemiology of injuries in US High School Girls' and NCAA Women's Basketball: 2004/05-2013/14. J Athl Train. 2017;52(6):S183.
5. DiStefano LJ, Dann CL, Chang CJ, Putukian M, Pierpoint LA, Currie DW, Knowles SB, Wasserman EB, Dompier TP, Comstock RD, Marshall SW, Kerr ZY. The first decade of web-based sports injury surveillance: descriptive epidemiology of injuries in US High School Girls' Soccer (2005–2006 through 2013–2014) and National Collegiate Athletic Association Women's Soccer (2004–2005 through 2013–2014). J Athl Train. 2018;53(9):880–92. https://doi.org/10.4085/1062-6050-156-17.
6. Kerr ZY, Lynall RC, Roos KG, Dalton SL, Djoko A, Dompier TP. Descriptive epidemiology of non-time-loss injuries in collegiate and high school student-athletes. J Athl Train. 2017;52(5):446–56. https://doi.org/10.4085/1062-6050-52.2.15.
7. Zuckerman SL, Wegner AM, Roos KG, Djoko A, Dompier TP, Kerr ZY. Injuries sustained in National Collegiate Athletic Association men's and women's basketball, 2009/2010–2014/2015. Br J Sports Med. 2018;52(4):261–68.
8. Salmon LJ, Russell VJ, Refshauge K, Kader D, Connolly C, Linklater J, Pinczewski LA. Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. Am J Sports Med. 2006;34(5):721–32.
9. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med. 2009;37(2):246–51.
10. Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, Consortium M, Spindler KP. Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: prospective analysis of 2488 primary ACL reconstructions from the MOON cohort. Am J Sports Med. 2015;43(7):1583–90. https://doi.org/10.1177/0363546515578836.
11. Wright RW, Dunn WR, Amendola A, Andrish JT, Bergfeld J, Kaeding CC, Marx RG, McCarty EC, Parker RD, Wolcott M, Wolf BR, Spindler KP. Risk of tearing the intact anterior cruciate ligament in the contralateral knee and rupturing the anterior cruciate ligament graft during the first 2 years after anterior cruciate ligament reconstruction: a prospective MOON cohort study. Am J Sports Med. 2007;35(7):1131–34.
12. Rahr-Wagner L, Thillemann TM, Pedersen AB, Lind MC. Increased risk of revision after anteromedial compared with transtibial drilling of the femoral tunnel during primary anterior cruciate ligament reconstruction: results from the Danish Knee Ligament Reconstruction Register. Arthroscopy. 2013;29(1):98–105. https://doi.org/10.1016/j.arthro.2012.09.009.
13. Wang D, Chiaia T, Cavanaugh JT, Rodeo SA. Team approach: return to play after anterior cruciate ligament reconstruction. JBJS Rev. 2019;7(1):e1. https://doi.org/10.2106/JBJS.RVW.18.00003.

Contents

Contributors

Kristin R. Archer, PhD, DPT Department of Orthopaedic Surgery, Vanderbilt University Medical Center, Nashville, TN, USA

Department of Physical Medicine and Rehabilitation, Vanderbilt University Medical Center, Nashville, TN, USA

Elanna K. Arhos, DPT Biomechanics and Movement Science Program, University of Delaware, Newark, DE, USA

Christopher A. Arrigo, PT, ATC Advanced Rehabilitation, Tampa, FL, USA

MedStar Sports Medicine, Lafayette Centre, Washington, DC, USA

Sue Barber-Westin, BS Noyes Knee Institute, Cincinnati, OH, USA

Cincinnati Sports Medicine and Orthopaedic Center, Cincinnati, OH, USA

Bruce Beynnon, PhD Department of Orthopaedics and Rehabilitation, Robert Larner College of Medicine, University of Vermont, Burlington, VT, USA

Jacob J. Capin, DPT Biomechanics and Movement Science Program, University of Delaware, Newark, DE, USA

Department of Physical Therapy, University of Delaware, Newark, DE, USA

Jorge Chahla, MD, PhD Department of Orthopaedics Surgery, Rush University Medical Center, Chicago, IL, USA

Brian J. Cole, MD Department of Orthopaedics Surgery, Rush University Medical Center, Chicago, IL, USA

Rogelio A. Coronado, PhD, PT Department of Orthopaedic Surgery, Vanderbilt University Medical Center, Nashville, TN, USA

Eileen A. Crawford, MD Division of Sports Medicine and Shoulder Surgery, Department of Orthopaedic Surgery, University of Michigan, Ann Arbor, MI, USA

Medsport, Ann Arbor, MI, USA

George J. Davies, DPT Physical Therapy Program, Georgia Southern University - Armstrong Campus, Savannah, GA, USA

Biodynamics and Human Performance Center, Savannah, GA, USA

Ian J. Dempsey, MD Department of Orthopaedics Surgery, Rush University Medical Center, Chicago, IL, USA

Emily Eichner, BA Department of Orthopaedics and Rehabilitation, Robert Larner College of Medicine, University of Vermont, Burlington, VT, USA

Dustin Grooms, PhD, ATC Athletic Training, Ohio University, Athens, OH, USA

School Applied Health Sciences & Wellness, Ohio University, Athens, OH, USA

College of Health Sciences and Professions, Ohio University, Athens, OH, USA

Ohio Musculoskeletal & Neurological Institute, Ohio University, Athens, OH, USA

Timothy P. Heckmann, PT Jewish Hospital Orthopaedic Sports Medicine and Rehabilitation, Cincinnati, OH, USA

Noyes Knee Institute, Cincinnati, OH, USA

Daniel Herman, MD, PhD Divisions of PM&R, Sports Medicine, and Research, Department of Orthopedics and Rehabilitation, University of Florida, Gainesville, FL, USA

Simone Herzberg, BS Department of Orthopaedic Surgery, Vanderbilt University Medical Center, Nashville, TN, USA

Luke Hughes, PhD Faculty of Sport, Health & Applied Science, St Marys University, London, UK

Katherine J. Hunzinger, MS Department of Kinesiology and Applied Physiology, University of Delaware, Newark, DE, USA

Interdisciplinary Program in Biomechanics and Movement Science, University of Delaware, Newark, Newark, DE, USA

Mininder S. Kocher, MD Division of Sports Medicine, Department of Orthopedics, Boston Children's Hospital, Boston, MA, USA

Harvard Medical School, Boston, MA, USA

The Micheli Center for Sports Injury Prevention, Waltham, MA, USA

Neal B. Naveen, BS Department of Orthopaedics Surgery, Rush University Medical Center, Chicago, IL, USA

Frank R. Noyes, MD Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

James Onate, PhD OSU Division of Athletic Training, The Ohio State University, Columbus, OH, USA

OSU Movement Optimization Prevention for Exercise Sustainment (MOvES), The Ohio State University, Columbus, OH, USA

OSU Movement Analysis & Performance Research Program, The Ohio State University, Columbus, OH, USA

Stanley D. and Joan H. Ross Center for Brain Health & Performance, The Ohio State University, Columbus, OH, USA

OSU Sports Medicine Research Institute, The Ohio State University, Columbus, OH, USA

OSU Human Performance Collaborative, The Ohio State University, Columbus, OH, USA

Johnny Owens, MPT Owens Recovery Science, INC, San Antonio, TX, USA

Stephen D. Patterson, PhD Faculty of Sport, Health and Applied Science, St Marys University, London, UK

Bryan L. Riemann, PhD, ATC Biodynamics and Human Performance Center, Savannah, GA, USA

Department of Health Sciences and Kinesiology, Georgia Southern University - Armstrong Campus, Savannah, GA, USA

May Arna Risberg, PT, PhD Norwegian Research Center for Active Rehabilitation, Department of Sports Medicine, Norwegian School of Sport Sciences, Oslo, Norway

Norwegian Research Center for Active Rehabilitation, Department of Orthopaedics, Oslo University Hospital, Oslo, Norway

Ian Shrier, MD Centre for Clinical Epidemiology, Jewish General Hospital, QC, Canada

Andrew Smith, DO Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

Lynn Snyder-Mackler, PT Biomechanics and Movement Science Program, University of Delaware, Newark, DE, USA

Department of Physical Therapy, University of Delaware, Newark, DE, USA

Taylor M. Southworth, BS Department of Orthopaedics Surgery, Rush University Medical Center, Chicago, IL, USA

Zach Sutton, PT, DPT Health Rehabilitation Centers, University of Florida, Gainesville, FL, USA

Charles Buz Swanik, PhD Department of Kinesiology and Applied Physiology, University of Delaware, Newark, DE, USA

Interdisciplinary Program in Biomechanics and Movement Science, University of Delaware, Newark, DE, USA

Tracy M. Tauro, BS Department of Orthopaedics Surgery, Rush University Medical Center, Chicago, IL, USA

Jessica L. Traver, MD Division of Sports Medicine, Department of Orthopedics, Boston Children's Hospital, Boston, MA, USA

Harvard Medical School, Boston, MA, USA

The Micheli Center for Sports Injury Prevention, Waltham, MA, USA

Kevin E. Wilk, DPT Sports Medicine, Champion Sports Medicine, Birmingham, AL, USA

Gary Wilkerson, PhD, ATC University of Tennessee at Chattanooga, Chattanooga, TN, USA

Edward M. Wojtys, MD Division of Sports Medicine and Shoulder Surgery, Department of Orthopaedic Surgery, University of Michigan, Ann Arbor, MI, USA

Abbreviations

ACI	Autologous chondrocyte implantation
ACL	Anterior cruciate ligament
ACL-QoL	Anterior Cruciate Ligament-Quality of Life
ACLR	Anterior cruciate ligament reconstruction
ACL-RSI	Anterior Cruciate Ligament-Return to Sport After Injury
ACT	Acceptance and commitment therapy
ADC	Apparent diffusion coefficient
AE	Athlete exposure
AM	Anteromedial
ANAM	Automated Neuropsychological Assessment Metrics
AP	Anteroposterior
BEAR	Bridge-enhanced anterior cruciate ligament repair
BFRT	Blood flow restriction training
bFGF	Basic fibroblast growth factor
BMI	Body mass index
BMPs	Bone morphogenetic proteins
BPTB	Bone-patellar tendon-bone
BW	Body weight
CKC	Closed kinetic chain
CNS	Central nervous system
CNTs	Computerized neurocognitive tests
cm	Centimeters
CogSport/CogState	Axon Sports Computerized Cognitive Assessment Tool
COM	Center of mass
COP	Center of pressure
COWA	Controlled word association
COX	Cyclooxygenase
CPG	Clinical practice guidelines
CPM	Continuous passive motion
CT	Computed tomography
DANA	Defense Automated Neurobehavioral Assessment
dGEMRIC	Delayed gadolinium-enhanced magnetic resonance imaging
DIS	Dynamic intraligamentary stabilization
DOC	Delaware-Oslo cohort

DTI	Diffusion tensor imaging
ECM	Extracellular matrix
EEG	Electroencephalography
EMG	Electromyographic or electromyography
EMS	Electrical muscle stimulation
ER	External rotation
ES	Effect size
FA	Fractional anisotropy
FAIR	From activity to injury to rehabilitation/reintegration
FGF	Fibroblast growth factors
FTA	Functional testing algorithm
GAG	Glycosaminoglycans
EGF	Epidermal growth factors
GRF	Ground reaction force
GRFV	Ground reaction force vector
rGRFV	Resultant ground reaction force vector
GRS	Global rating score
H/Q	Hamstrings/quadriceps
HR	Hazard ratio
HSS	Hospital for Special Surgery
HT	Hamstring tendon
IC	Initial contact
ICC	Intraclass correlation coefficients
IKDC	International Knee Documentation Committee
ImPACT	Immediate Post-concussion Assessment and Cognitive Testing
IPC	Ischemic preconditioning
IR	Internal rotation or incidence rates
IR/ER	Internal rotation/external rotation
ITB	Iliotibial band
JPS	Joint position sense
KE	Knee extensor
KF	Knee flexor
KOOS	Knee Injury and Osteoarthritis Outcome
KT and KT-2000	Knee arthrometer
LEFT	Lower Extremity Functional Test
LOP	Limb occlusion pressure
LSI	Limb symmetry index
M	Meters
MACI	Matrix-induced autologous chondrocyte implantation
MAT	Meniscal allograft transplantation
min	Minutes
mo	Month
MOON	Multicenter Orthopedic Outcomes Network
MRI	Magnetic resonance imaging
ms	Milliseconds
MSCs	Mesenchymal stem cells
MSI	Musculoskeletal injuries

MUA	Manipulation under anesthesia
MVIC	Maximal volitional isometric contraction
N	Newton
NA	Not available
NAR	Norwegian Arm
NBA	National Basketball Association
NCAA	National Collegiate Athletic Association
NCACL	Noncontact anterior cruciate ligament
NFL	National Football League
NHL	National Hockey League
NIHTB-CB	National Institutes of Health Toolbox Cognition Battery
NKLR	Norwegian National Knee Ligament Registry
Nm	Newton meters
NMES	Neuromuscular electrical stimulation
NS	Not significant (statistically)
NSAIDs	Nonsteroidal anti-inflammatories
NWBE	Non-weight-bearing exercises
OA	Osteoarthritis
OAT	Osteochondral autograft transplant
OCA	Osteochondral allografts
OKC	Open kinetic chain
OPG	Osteoprotegerin
OR	Odds ratio
PA	Posteroanterior
PDGF	Platelet-derived growth factors
PDLLA	Poly-d-lactide
PEC	Parallel elastic components
PL	Posterolateral
PLLA	Poly-l-lactide
PMN	Polymorphonuclear
PRiSM	Pediatric Research in Sports Medicine
PRP	Platelet-rich plasma
PT	Patellar tendon
PTBML	Post-traumatic bone marrow lesions
PTOA	Post-traumatic osteoarthritis
QI	Quadriceps index
QOL	Quality of life
QT-PB	Quadriceps tendon-patellar bone
RCT	Randomized controlled trial
RFD	Rate of force development
RM	Repetition max
RR	Relative risk
ROM	Range of motion
RTS	Return to sport
s	Seconds
SEC	Series elastic components
SSC	Stretch-shortening cycle

SMCL	Superficial medial collateral ligament
StARRT	Strategic Assessment of Risk and Risk Tolerance
STG	Semitendinosus-gracilis
STIR	Short tau inversion recovery
T (as in 3-T)	Tesla
TGF	Transforming growth factors
TIMPs	Tissue inhibitors of metalloproteinases
TKA	Total knee arthroplasty
TMS	Transcranial magnetic stimulation
TSK	Tampa Scale for Kinesiophobia
US	United States
UTE	Ultrashort echo time
vGRF	Vertical ground reaction force
VLO	Vastus lateralis obliquus
VMO	Vastus medialis oblique
VO_2max	Maximal oxygen uptake
WB	Weight bearing
wk	Week
x	Times
yr	Year
3-D	Three dimensional
2-D	Two dimensional

Part I

Problems and Barriers for Successful Return to Sport

1

Advantages and Potential Consequences of Return to Sport After ACL Reconstruction: Quality of Life, Reinjury Rates, and Knee Osteoarthritis

Frank R. Noyes and Sue Barber-Westin

1.1 Introduction

The majority of patients who undergo anterior cruciate ligament (ACL) reconstruction are athletes <25 years of age [1]. While there are several major goals of surgery, returning these individuals to their desired sport is paramount for patient satisfaction [2–8] and is the main motivating factor for patients to undergo surgery and months of rehabilitation. Physicians and others involved with patient care often believe return to sports (RTS) is one of the most important outcome criteria after ACL reconstruction [9]. The ultimate RTS goals vary widely and include returning professional athletes back to their careers, allowing collegiate athletes to receive scholarships, providing high school athletes a chance to play additional seasons, and returning recreational athletes back to their desired active lifestyle. Although historic rates of RTS have been acceptable, this topic has come under increased scrutiny due to high reinjury rates recently reported (to the ACL in either knee) upon return to athletics after surgery [10].

In addition to reinjury rates, several barriers that prevent or delay full RTS have recently come under rigorous investigation. These include fear, anxiety, depression, preoperative stress, motivation, self-esteem, locus of control, and self-efficacy [3, 7, 11–26]. Persistent knee symptoms of pain, swelling, stiffness, and instability may also hamper the expected progress of rehabilitation and negatively affect the time to RTS [18, 27–29].

Even though many studies have reported significant correlations of return to high-risk sports with ACL reinjuries, few have documented the results of rehabilitation in terms of restoration of normal muscle strength, balance, proprioception, and other neuromuscular indices required for return to high-risk activities that require pivoting, cutting, and jumping/landing. In addition, several studies have shown that changes in neurocognitive function and cortical activity occur after ACL injury and reconstruction [30–37]. The question of whether modern rehabilitation programs effectively resolve these impairments remains to be answered [38, 39]. Therefore, reinjuries may not be due simply to participation in high-risk activities; failure to restore multiple indices to normal (in both knees) may be one major source of this problem, and this will be explored later in this textbook.

The question of what factors play a role in the development of knee osteoarthritis (OA) after ACL reconstruction remains under study, with the exception of meniscectomy. Nearly every long-term study has reported a statistically significant correlation between meniscectomy (per-

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_1

formed either concurrently or after the ACL reconstruction) and moderate-to-severe radiographic evidence of OA [40–48]. Other factors that may influence the development of knee joint OA include preexisting chondral damage, severe bone bruising, biochemical alterations after the injury, older patient age, elevated body mass index (BMI), excessive uncorrected varus or valgus lower limb malalignment, damage of other knee ligaments, failure of the reconstruction to restore knee stability, serious complications (such as infection, arthrofibrosis), and poor quadriceps strength [47, 49–54]. Whether return to high-impact sports after ACL reconstruction increases the rate of development of knee OA is unknown at present. Regardless of the cause, the development of symptomatic OA is especially concerning in young athletic individuals, in whom rates of total knee arthroplasty (TKA) continue to rise rapidly. In 2013, Weinstein et al. [55] estimated that over 1.5 million individuals aged 50–69 years had undergone TKA in the USA, tripling the number compared with the proceeding decade. With TKA survival rates of 20 years, many younger individuals may require a revision arthroplasty.

1.2 Quality of Life and Patient Satisfaction: Correlation with Return to Sport

One major goal of ACL reconstruction is to return patients to their desired sports activity level. Interestingly, a review published in 2015 found that, in 119 ACL-reconstruction studies, only 24% provided return to preinjury sports activity data [56]. The authors recommended enhanced reporting of these data due to the high level of relevance of RTS for both patients and clinicians. In the same year, a survey of 1779 orthopedic medical professionals reported a consensus of six measures believed important for successful outcome 2 years after ACL reconstruction [9]. These measures included no giving-way (indicated by 96.4% of respondents), RTS as indicated by playing 2 seasons at the preinjury level (92.4%), quadriceps strength symmetry >90% (90.3%), absence of joint effusion (84.1%), patient-reported outcomes (83.2%), and hamstrings strength symmetry >90% (83.1%).

Ardern et al. [2] questioned whether satisfaction of knee function according to the *patient* was associated with different measures, including psychological factors and personal opinion of knee function. These authors followed 177 ACL-reconstructed patients a mean of 3 years postoperatively, of whom 44% were satisfied with their outcome, 28% mostly satisfied, and 28% dissatisfied. There was a significantly greater percentage of patients in the satisfied group that returned to their preinjury sports level compared with the other groups (61%, 29%, and 22%, respectively, $P < 0.0001$). Participants who had returned to their preinjury activity level had 3 times increased odds of being satisfied (versus mostly satisfied or dissatisfied). The other two significant associations with satisfaction were knee-related self-efficacy and quality of life (QOL).

Another study performed a cross-sectional comparison of patients who underwent either operative or conservative treatment for acute ACL ruptures [57]. At 1 year post-injury or postoperative, 350 ACL-deficient knees and 350 ACL-reconstructed knees completed the Knee Injury and Osteoarthritis Outcome Score (KOOS). The ACL-reconstructed group had higher scores for pain, activities of daily living, sports, and quality of life 1 year postoperatively (Table 1.1). The authors concluded that patients who elected ACL reconstruction had superior

Table 1.1 KOOS scores in ACL-deficient and ACL-reconstructed knees at 1 year

KOOS domain	ACL-deficient	ACL-reconstructed	Mean difference (*P* value)
Symptoms	73.7 ± 18.4	76.3 ± 18.5	2.6 (NS)
Pain	80.5 ± 16.7	84.5 ± 16.3	4.0 (<0.05)
Activities of daily living	88.0 ± 15.1	91.3 ± 14.0	3.4 (<0.05)
Sport	54.5 ± 29.8	66.9 ± 26.6	12.4 (<0.05)
Quality of life	47.1 ± 24.3	60.3 ± 23.5	13.2 (<0.05)

KOOS knee injury and osteoarthritis outcome score, *NS* not significant outcomes for knee symptoms, function, and quality of life that remained for at least 5 years postoperatively.

Filbay et al. [4] studied QOL and psychological health outcomes in 162 patients who had residual knee pain, symptoms, or functional limitations a mean of 9 years (range, 5–20) postoperative. These investigators found that RTS was related to better knee-related KOOS and general health-related QOL (AQoL-8D) scores. In this study, 39% returned to competitive sports, 28% returned at a lower level of competition, and 32% did not return. When asked what activities they would consider most important to participate in (in the absence of knee pain), 80% of the patients indicated sports or exercise; 14%, family duties; 4%, social activities; and 2%, work duties. This high rate of patients that preferred sports/exercise over all other activities indicates the high priority athletics had in this cohort many years following their ACL injury and surgery.

Nwachukwu et al. [7] surveyed 231 patients a mean of 3.7 years following ACL reconstruction and reported that 87% had RTS and 85.4% were very satisfied with the outcome of the operation. A significantly greater number of patients who RTS were very satisfied with their outcome compared with those who did not return ($P < 0.001$). It is important to note that only 43.6% of the athletes played with unlimited effort and performance and no pain. The use of a patellar tendon autograft was associated with a significantly increased odds of returning to play compared with use of an allograft (odds ratio [OR] = 5.6; $P = 0.02$).

Faltstrom et al. [17] conducted a short-term study (mean follow-up, 1.5 years) in 182 female soccer players who underwent ACL STG autograft reconstruction. The survey study found that 52% were currently playing soccer, 80% at the same or higher preinjury level and 20% at a lower level. Players that returned had significantly higher scores compared with those who had not returned on all KOOS subscales and the ACL-Quality of Life scale. In addition, psychological readiness and motivation to return to sport correlated with return to preinjury levels. The negative effects of fear of reinjury and poor motivation on RTS are further discussed in Chap. 2.

Kocher et al. [5] followed a cohort of 201 patients whose mean age was 28.6 years (range, 14.4–60) an average of 3 years after primary ACL reconstruction. Patients were found to be significantly less satisfied with the outcome of surgery if they had a lower level of sports activity ($P < 0.001$) and if they had difficulty with specific athletic functions such as running, jumping, cutting, and twisting ($P < 0.001$). In this study, 75 patients (37%) were participating in sports with no limitations.

1.3 Reinjury Rates After ACL Reconstruction

The published rates of either reinjuring an ACL-reconstructed knee or sustaining an ACL rupture on the contralateral knee vary widely (Table 1.2) [58–83]. One problem is the definition of ACL failure; some studies consider only those knees that required ACL revision reconstruction (or reconstruction of the contralateral ACL) as failures, while others include knees in which a pivot shift grade 2–3 and/or Lachman grade 2–3 is detected clinically. Large registry studies or those that involved meta-analyzed data typically only used the number of ACL revision cases to calculate failure rates [65, 69, 76, 79, 81, 84]. There are many potential causes of ACL graft failure other than reinjuries that have been discussed in detail elsewhere [85–90]. The reinjury and failure rate data in Table 1.2 should therefore be interpreted cautiously.

Many studies have cited that the most frequent factors that appear to cause graft failure or injury to the contralateral ACL are younger patient age, return to cutting/pivoting sports, and use of an allograft. In a meta-analysis of data from 19 studies, Wiggins et al. [62] reported, in athletes <25 years of age who returned to high-risk sports, a pooled secondary ACL injury rate (to either knee) of 23%. In a group of 1415 patients who underwent ACL autograft reconstruction, Shelbourne et al. [60] reported the risk of subsequent injury to either knee was 17% for patients

Table 1.2 Rates of reinjury in ACL-reconstructed and contralateral knees

Study	Mean follow-up years	ACL graft[a] (no.)	Failed ACL reconstruction[b] (%)	Injured ACL contralateral knee (%)	Reinjuries associated with sports?	Factors associated with reinjuries, ACL graft failures
Salmon [58]	20	Hamstring adolescents (39)	38	13	Yes, nearly all associated with sports for both ipsilateral and contralateral	Age <18 years, posterior tibial slope ≥12° for ACL-reconstructed knee Posterior tibial slope ≥12° for contralateral knee
		Hamstring adults (161)	14	11		
		Total (200)	18.5	11		
Morgan [59]	16.6	Hamstring (194)	19.5	17.5	Yes, cutting, pivoting sports for contralateral knee reinjuries	Family history ACL injury for ACL-reconstructed knee Male gender for contralateral knee
		BPTB (48)	8	29		
		Total (242)	17	20		
Shelbourne [60]	5	BPTB (1,415)	4	5	Yes, participation in basketball or soccer for injuries to either knee.	Age <18 years, female gender for ACL-reconstructed knee Age <18 years, female gender <18 years for contralateral knee
Takazawa [61]	4.7	ST and Telos artificial ligament	16	7	All rugby players	Age <20 years for ACL-reconstructed knee
Wiggins [62]	4.2	9098 <25 years age	10	11	Yes, return to cutting, pivoting sports	Age <25 years for both knees
		913 <25 years age, returned high-risk sports	10	12		
		Total 72,054	7	8		
Grindem [63]	2	BPTB (33), hamstring (67)	Overall 8	Overall 2	Yes, return level I sports 4.32 times higher reinjury rate than other sport levels	Quadriceps strength deficit for ACL-reconstructed knee
Webster [64]	3	Hamstring (561)	4.5	7.5	Yes, return to cutting, pivoting sports for either knee	Age <20 years, contact mechanism for injury, family history for ACL-reconstructed knee. Age <20 years, family history for contralateral knee
Kaeding [65]	2	BPTB (1131)	3.2	NA	Yes, higher preinjury activity levels for reinjuries to either knee	Allografts for ACL-reconstructed knee Younger age for both knees
		Hamstring (891)	4.6	NA		
		Allograft (466)	6.9	NA		
		Total (2488)	4.4	3.5		
Kyritsis [66]	NA	BPTB (50)	14	Overall 7	Yes, all pro athletes	Low H:Q ratio 60°/s, athletes did not meet discharge criteria for ACL-reconstructed knee
		Hamstring (108)	17.5			

Table 1.2 (continued)

Study	Mean follow-up years	ACL graft[a] (no.)	Failed ACL reconstruction[b] (%)	Injured ACL contralateral knee (%)	Reinjuries associated with sports?	Factors associated with reinjuries, ACL graft failures
Kamath [67]	NA	Graft NA, $N = 89$	9	15	All collegiate athletes	Athletes that had ACL reconstruction before entering college had higher incidence of graft failure and contralateral ACL tears
Lefevre [68]	1	Hamstring primary (468), BPTB primary (27), hamstring revision (18), BPTB revision (29)	Overall 1.4	Overall 0	Yes, all reinjuries (7 in primary group, 1 in revision group) during sports	None
Faltstrom [69]	5	Hamstring (20,824)	4.3	3.8	Yes for soccer	Age <16 years, age 16–25, surgery <90 days from injury, injured playing soccer for either knee
Ardern [70]	2	Hamstring (122)	4	2	Yes	Not assessed
Myklebust [71]	7.8	Various grafts	22	9	Yes, all while playing team handball	Not assessed
Mohtadi [72]	2	BPTB (110)	17	5	Not significantly related to sports	Age <27 years for ACL-reconstructed knee
		Hamstring (110)	26	5		
		Double bundle (110)	28	5		
Park [73]	4.5	Hamstring (296)	4	NA	Not related to sports	Grafts <8 mm in diameter.
Thompson [74]	20	BPTB (90)	10	30	Not assessed	Male gender, age ≤18 years, tunnel placement for ACL-reconstructed knee Age ≤18 years, BTB graft for contralateral knee
		Hamstring (90)	18	14		
Pinczewski [75]	10	BPTB (90)	8	22	Not assessed	Laxity for ACL-reconstructed knee Age <21 years, BPTB graft for contralateral knee
		Hamstring (90)	13	10		
Hettrich [76]	6	BPTB (469)	4.1	NA	Not assessed	Allografts, younger age
		Hamstring (343)	6.1	NA		
		Allograft (168)	21.2	NA		
		Total (980)	7.7	6.4		

(continued)

Table 1.2 (continued)

Study	Mean follow-up years	ACL graft[a] (no.)	Failed ACL reconstruction[b] (%)	Injured ACL contralateral knee (%)	Reinjuries associated with sports?	Factors associated with reinjuries, ACL graft failures
Schlumberger [77]	5	Hamstring (2467)	3	3	Not assessed	Male gender, age <25 years for ACL-reconstructed knee
Webster and Feller [78]	5	Hamstring (316) All <20 yrs age	18	18	Not assessed	Male gender, male age <18 years for ACL-reconstructed knee
Persson [79]	4	BPTB (3428)	2	NA	Not assessed	STG autograft, younger age
		Hamstring (9215)	5.1	NA		
		Total (12643)	4.2	NA		
Kamien [80]	>2	Hamstring (98)	15	NA	Not assessed	Age ≤25 years
Maletis [81]	2.4	BPTB (4231)	1.9	1.9	Not assessed	Allograft or STG autograft, male gender, younger age, BMI ≥25 for ACL-reconstructed knee Female gender, younger age, BPTB autograft for contralateral knee
		Hamstring (5338)	2.4	1.8		
		Allograft (7116)	2.8	1.5		
		Total (16,685)	2.5	1.9		
Leys [82]	15	BPTB (90)	8	26	Not assessed	Male gender, non-ideal tunnel position for ACL-reconstructed knee Age <18 years, BPTB graft for contralateral knee
		Hamstring (90)	17	12		

ACL anterior cruciate ligament, *BPTB* bone-patellar tendon-bone, *HR* hazards ratio, *ST* semitendinosus
[a]Autograft unless otherwise indicated
[b]Fully positive pivot shift and/or Lachman tests, Grade C or D International Knee Documentation Committee ligament grade, >5 mm on knee arthrometer testing, or required ACL revision

<18 years of age compared with 7% for patients 18–25 years and 4% for patients >25 years. These authors attributed the reinjuries to the high-risk sports patients had returned to, with basketball and soccer accounting for 67% of the reinjuries. Andernord et al. [84] reported data on 16,930 patients from the Swedish National Knee Ligament Register and found in both males and females a significantly increased twofold risk of revision surgery with ages 13–19 years ($P < 0.001$). In a separate study, Andernord et al. [91] reported a significantly increased twofold to threefold risk of contralateral ACL reconstruction in patients less than 20 years of age ($P < 0.001$).

Dekker et al. [83] followed 85 patients who were <18 years of age at the time of ACL autograft reconstruction a mean of 4 years postoperatively. A majority (91%) returned to sports activities; however, 32% suffered a subsequent ACL tear (19% ipsilateral graft tear, 13% contralateral ACL tear, and 1% both knees) a mean of 2.2 years postoperatively. The only significant risk factor associated with reinjury was earlier return to sport ($P < 0.05$). Longer times before returning to athletics were protective against a second ACL injury (hazard ratio per month, 0.87 for each 1-month increase).

Faltstrom et al. [92] followed 117 female soccer players (mean age, 19.9 ± 2.5 years) a mean of 2 years after primary ACL reconstruction and compared reinjury rates, proportion of players who stopped playing soccer, and patient satisfaction with a matched group of uninjured players. The ACL-reconstructed group had nearly a fivefold higher rate of new ACL injuries (29 versus 8, rate ratio 4.82, $P < 0.001$), a higher rate of players who stopped playing soccer (62% versus 36%, $P = 0.001$), and a lower satisfaction rate (47% versus 87%).

Several investigations have reported discouraging percentages of athletes who RTS even though muscle strength and neuromuscular function appeared to be restored to normal levels [28, 29, 93–96]. A meta-analysis of 69 articles involving 7556 athletes reported that only 65% returned to their preinjury sports level and 55% returned to competitive sports [94]. Factors associated with RTS included symmetrical hopping performance, younger age, male gender, playing elite sports, and having a positive attitude. A study of 205 soccer players reported that only 54% returned to the sport a mean of 3.2 years postoperatively [29]. Of those that returned, 39% experienced pain, 43% had stiffness, and 42% reported instability during or after physical activity. Male gender, no cartilage injury, and no pain during physical activity were associated with greater odds of RTS. An investigation of 99 athletes reported that although 92% returned to sports, only 51% returned to their preinjury level [23]. Factors associated with RTS in this study included female gender and higher scores on the International Knee Documentation Committee (IKDC) Subjective Knee scale and the Lysholm scale. Rosso et al. [28] reported that, although 90% of 161 patients RTS after primary ACL reconstruction, only 58% did so at the preinjury level. The main reasons for not returning were knee symptoms (37%), personal reasons (30%), or both (29%).

A meta-analysis that assessed RTS and reinjury rates of 1008 children and adolescents (aged 6–19) from 19 studies reported a pooled return to preinjury activity level in 79% (range, 41–100%) [97]. ACL reinjury rates were provided for 717 patients, 13% of whom sustained ACL graft ruptures. Contralateral ACL rupture rates were provided for 652 knees, 14% of whom sustained injuries. Ten of the studies reported that the majority of injuries occurred during sports activities.

Critical Points

- Long-term failure rates vary widely (2–32%).
- Factors correlated with ACL graft failure: younger age, high sports activity level, vertical graft angle, and use of a small STG autograft or allograft.
- Contralateral ACL at risk for rupture, higher than ACL graft in some studies.

1.4 Factors Involved in the Development of Knee Osteoarthritis After ACL Surgery

Long-term clinical studies documenting radiographic OA after ACL reconstruction show high variability in the percent of knees that develop moderate or severe joint damage (Table 1.3) [40, 41, 45–48, 75, 99–101, 103–106, 108, 110–114]. These studies most frequently used weight-bearing anteroposterior (AP) and posteroanterior radiographs (Fig. 1.1), as well as lateral and Merchant, to determine the presence and severity of OA, although a few used MRI [110, 111, 114, 116, 117] or computed tomography [118]. The two most commonly used radiographic rating systems to classify OA are the Kellgren-Lawrence (K-L) [119] and the IKDC system [120]. It is also important to note that few investigators have determined if OA is accompanied by pain, swelling, and impaired knee function. The longest clinical studies published to date have followed patients for 16–24.5 years postoperatively [102, 121–123]. As investigations obtain longer follow-up periods, one may speculate that the OA findings will become more severe and correlate

Table 1.3 Prevalence of radiographic osteoarthritis in long-term ACL reconstruction studies

Study	No. of patients	Mean follow-up year	ACL graft[a] (failure rate[b])	OA KL grade 2–3 IKDC grade abnormal, severely abnormal	OA related to sports or activity level resumed postoperatively?	Statistically significant risk factors for OA unrelated to sports
Shelbourne [98]	423	22.5	BPTB (1%)	29%	Unknown	Lack of normal knee flexion or extension, medial meniscectomy, older age
Gerhard [45]	63	16	BPTB (3%)	23%	Unknown	Meniscectomy
Oiestad [99]	181	12.3	BPTB (8%)	26%	Unknown	Increased age, poor quadriceps strength
Holm [100]	53	11.8	BPTB (21%)	80%	Unknown	Meniscectomy, chronicity of injury
Ahn [40]	117	10.3	BPTB (9%)	31%	Unknown	Partial meniscectomy and sagittal tibial tunnel position in medial compartment, BMI in lateral compartment
Murray [101]	83	13	BPTB (17%)	40%	Unknown	Meniscectomy, pre-existing chondral damage
Shelbourne and Gray [48]	502	14.1	BPTB (1%)	23% in patients with bilateral meniscectomies 4% in patients with intact menisci	Hypothesized	Meniscectomy, preexisting chondral damage
Pernin [102]	100	24.5	BPT + iliotibial band extra-articular procedure (20%)	54%	Unknown	Meniscectomy, preexisting chondral damage, time to surgery, higher age at injury and surgery
Inderhaug [103]	83	10.2	Hamstring (20%)	8%	Unknown	Meniscectomy
Salmon [58]	200	20	Hamstring (18.5%)	17%	Unknown	NA
Struewer [104]	52	10.2	Hamstring (3%)	25%	Unknown	Increased anterior tibial displacement
Streich [105]	40	10	Hamstring (8%)	7%	Unknown	Positive pivot shift, high BMI
Janssen [106]	88	10	Hamstring (NA)	54%	Unknown	Medial meniscectomy, age ≥30 years, preexisting chondral damage
Thompson [74]	180	20	BPTB (10%) Hamstring (18%)	BPTB 20% Hamstring 13%	Unknown	Graft type (BPTB), further surgery
Bjornsson [107]	147	16	BPTB (7%) Hamstring (8%)	BPTB 49% Hamstring 41%	Unknown	NA

Table 1.3 (continued)

Study	No. of patients	Mean follow-up year	ACL graft[a] (failure rate[b])	OA KL grade 2–3 IKDC grade abnormal, severely abnormal	OA related to sports or activity level resumed postoperatively?	Statistically significant risk factors for OA unrelated to sports
Sanders [108]	600	13.7	BPTB, hamstring, or allograft (NA)	8.5%	Unknown	Age >21 at injury, meniscectomy, preexisting chondral damage, use of allograft
Cantin [42]	589	11.9	BPTB (NA) Hamstring (NA)	Overall 19%	Unknown	Age >34 at injury, residual laxity (IKDC grade C or D), meniscectomy
Barenius [41]	134	14	BPTB (4%) ST (5%)	BPTB 55% ST 70%	Manual labor	Meniscectomy, age at follow-up, BMI ≥ 25 kg/m^2, positive pivot shift
Ferretti [109]	140	10.5	Hamstring isolated (14%) or combined with EA (0%)	Hamstring 18% Hamstring + EA 14%	Unknown	Meniscectomy for STG isolated group only

AP anteroposterior, *auto* autograft, *BMI* body mass index, *BPTB* bone-tendon-bone, *EA* extra-articular, *IKDC* Internal Knee Documentation Committee, *KL* Kellgren-Lawrence, *NA* not available, *OA* osteoarthritis, *ST* semitendinosus

[a]Autografts unless otherwise indicated

[b]ACL failure rate: graft rupture, knee arthrometer >5 mm, or pivot shift grade 2–3

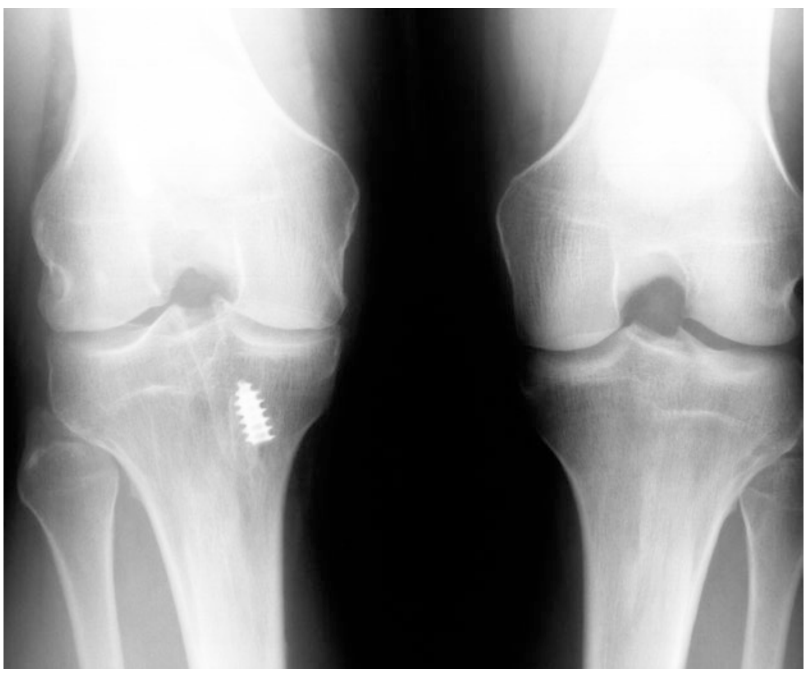


Fig. 1.1 Standing radiographs of a patient 14 years after a right ACL reconstruction and subsequent medial meniscectomy. The pivot-shift test was negative, indicating a stable reconstruction. However, narrowing to the medial tibiofemoral compartment is evident and the patient demonstrated 2° of varus alignment (Reprinted from Noyes and Barber-Westin [115])

with clinical symptoms such as loss of extension and swelling with daily activities.

Studies have shown that, regardless of the outcome of ACL reconstruction in terms of restoration of knee stability, meniscectomy accelerates degenerative joint changes [40, 41, 45–48, 124, 125]. Claes et al. [43] systematically reviewed 16 long-term ACL reconstruction studies (follow-up range, 10–24.5 years) involving 1554 subjects. The investigators reported that the estimate for the prevalence of moderate to severe OA (IKDC ratings of C or D) for all patients was 27.9%. The prevalence of OA was 16.4% in patients with isolated ACL injuries and 50.4% in patients with concurrent meniscectomy (OR 3.54).

Barenius et al. [41] followed 164 patients a mean of 14 years after ACL reconstruction and reported symptomatic OA (K-L grade ≥2) in 57% of ACL-reconstructed knees compared with 18% of contralateral knees. Statistically significant risk factors for medial tibiofemoral OA were BMI ≥25 kg/m^2 at follow-up (OR 3.3), manual labor (OR 3.2), positive pivot shift at 2-year follow-up (OR 2.5), and medial meniscectomy (OR 4.2). Statistically significant risk factors for lateral tibiofemoral OA were lateral meniscectomy (OR 5.1) and use of a B-PT-B autograft (OR 2.3). Statistically significant risk factors for patellofemoral OA were BMI ≥25 kg/m^2 at follow-up (OR 3.5) and medial meniscectomy (OR 2.3). There was no significant difference in the prevalence of OA between the two graft types.

We conducted a systematic review of the treatment of meniscus tears during ACL reconstruction of studies published from 2001 to 2011 [126]. Data on 11,711 meniscus tears (in 19,531 patients) from 159 studies showed that 65% were treated by meniscectomy; 26%, by repair; and 9%, by no treatment. This was concerning because many meniscus tears can be successfully treated by repair, thereby salvaging this important structure.

It is important to note that there are many factors other than meniscectomy that may influence the development of knee joint OA, including preexisting chondral damage, severe bone bruising, biochemical alterations in the knee joint after the injury, older patient age, elevated BMI, failure of the reconstruction to restore normal AP displacement, complications (such as infection, arthrofibrosis), and poor quadriceps strength [47, 49–54]. In many studies, these variables are not controlled for, making reaching conclusions on these factors difficult.

Occult injuries to the bone, commonly referred to as bone bruises, occur with ACL ruptures in 80–100% of knees (Fig. 1.2) [127–133]. Occult osteochondral lesions vary, and therefore, the relationship between the presence of these injuries with ACL ruptures and subsequent OA remains unclear. Several studies have reported that bone bruises resolve with time [110, 132, 134]. Conversely, Frobell [134] followed 61 consecutive patients who had acute ACL injuries with MRI within 4 weeks of the injury and then 2 years later. Subjects were treated either with early ACL reconstruction (34 subjects), delayed ACL reconstruction (11 subjects), or rehabilitation alone (16 subjects). Posttraumatic bone marrow lesions noted in the lateral tibiofemoral compartment resolved in 57 of 61 knees by 2 years after the ACL injury. However, new lesions developed in the lateral tibiofemoral joint for unknown reasons in one-third of the population, and significant thinning of the cartilage in the trochlea was noted that was not detected during the baseline MRI. Evidence does exist that the most severe injuries are associated with future

Fig. 1.2 Bone bruise on MRI following rupture of the ACL

cartilage degeneration, and they therefore should be considered part of the sequela of post-traumatic OA.

A few studies that longitudinally followed patients with acute ACL ruptures for several years demonstrated a strong potential for joint deterioration [54, 131, 134]. For instance Potter et al. prospectively followed 40 patients who underwent baseline MRI within 8 weeks of the injury and again 7–11 years later [131]. The MRI evaluation used a cartilage-sensitive, pulse sequence evaluation with T2 techniques which have shown increased ability to detect traumatic chondral injuries. None of the patients had concurrent damage to the menisci or other knee ligaments or an articular cartilage lesion rated as Outerbridge grade 3 or higher. ACL reconstruction was performed in 28 patients, while no surgery was done in 14. At baseline, all knees had an MRI-detectable cartilage injury, most severely over the lateral tibial plateau. Regardless of surgical intervention, by 7–11 years after injury, the risk of cartilage damage as viewed on MRI for the lateral femoral condyle was 50 times that of baseline, 30 times for the patella, and 18 times for the medial femoral condyle. The nonsurgical group had a significantly higher OR effect of cartilage loss over the medial tibial plateau compared with the surgical group.

ACL ruptures create biochemical alterations in the knee joint which many investigators hypothesize play a major role in the development of OA [135–150]. The sequence of events begins immediately after the injury and continues for years thereafter (Table 1.4) [135, 136, 149]. The injury causes collagen rupture, joint hemarthrosis, subchondral bone edema, elevated glycosaminoglycan (GAG) levels, and cell necrosis. In the ensuing months, the inflammatory process (indicated by elevated levels of several cytokine mediators such as IL-1β, IL-6, and tumor necrosis factor α [TNFα]), decrease in lubricin concentrations, release of enzymes, production of metalloproteinase (MMP), degradation of the extracellular matrix and proteoglycans, chondrocyte apoptosis, and cell death all contribute to articular cartilage deterioration.

Table 1.4 Pathogenesis of posttraumatic articular cartilage deterioration after ACL injury

Initial effects of ACL injury • Rupture of collagen • Separation of cartilage from subchondral bone • Edema of subchondral bone (bone bruise) • Hemarthrosis (intraarticular joint bleeding) • Elevated levels of GAG • Cell necrosis
Sub-acute (months) • Increased levels of inflammatory cytokines mediators, including IL-1β, IL-6, TNFα • Release of enzymes and production of MMP, including MMP-1, MMP-3, MMP-13 • Release of cartilage proteoglycan fragments, type II collagen • Decreased levels of lubricin (lubricants) • Degradation of proteoglycans • Chondrocyte apoptosis (death)
Chronic (years) • Elevated levels TNFα • Joint tissue remodelling • Articular cartilage deterioration, loss

GAG glycosaminoglycan, *MMP* metalloproteinase, *TNFα* tumor necrosis factor α
Reprinted from Noyes and Barber-Westin [151]

Our analysis of current long-term studies provided no answer regarding the potential deleterious effect of returning to high athletic activity levels on subsequent risk of symptomatic OA. One may hypothesize that knees with intact menisci and no other ligament damage (that do not sustain reinjuries) will have no statistically significant increased risk for symptomatic OA compared with matched controls. The need to preserve meniscal function remains paramount for the long-term welfare of the joint, and we have long advocated meniscal repair for tears in the red/red (periphery) and red/white (central) regions (Fig. 1.3) [152–156]. Complex tears are evaluated on an individual basis for repair potential (Fig. 1.4). The indications and contraindications for meniscus repair procedures have been discussed in detail elsewhere [153]. Our long-term study (10–22 years) of single longitudinal meniscus repairs that extended into the central region in patients ≤20 years of age showed the potential longevity of this procedure [155]. Twenty-nine repairs were evaluated; 18 by follow-up arthroscopy, 19 by clinical evaluation, 17 by MRI, and 22 by weight-bearing pos-

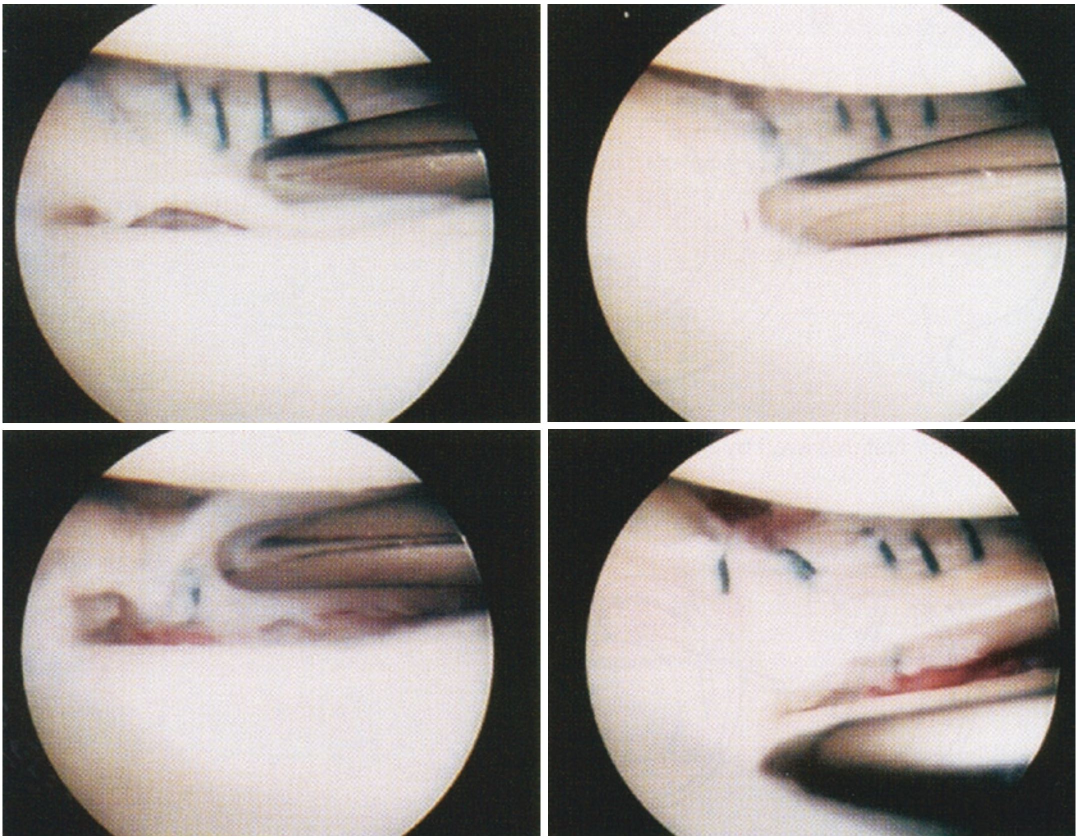


Fig. 1.3 Meniscus repair instead of meniscectomy to preserve knee joint function. A longitudinal meniscal tear site demonstrates some fragmentation inferiorly. This tear required multiple superior and inferior vertical divergent sutures to achieve anatomic reduction (Reprinted from Noyes and Barber-Westin [152])

teroanterior radiographs. A 3 T MRI scanner with cartilage-sensitive pulse sequences was used and T2 mapping was performed (Fig. 1.5). We found that 18 (62%) of the meniscus repairs had normal or nearly normal characteristics. Six repairs (21%) required arthroscopic resection, two had loss of joint space on radiographs, and three that were asymptomatic failed according to MRI criteria. There was no significant difference in the mean T2 scores in the menisci that had not failed between the involved and contralateral tibiofemoral compartments. There were no significant differences between the initial and long-term evaluations for pain, swelling, jumping, patient knee condition rating, or the Cincinnati rating score. The majority of patients were participating in sports without problems, which did not affect the failure rate. The outcomes support the recommendation in younger active patients to spend as much time and attention to a meniscus repair as a concurrent ACL reconstruction, as the eventual function of the knee joint is equally dependent on the success of the both structures

Critical Points

- Majority OA mild or moderate; presence of associated symptoms not reported in most studies.
- Meniscectomy correlates with radiographic evidence of osteoarthritis (OA) in nearly all long-term studies in which cohorts are sorted according to intact versus meniscectomized knees.
- Other risk factors associated with OA after ACL reconstruction include preexisting chon-

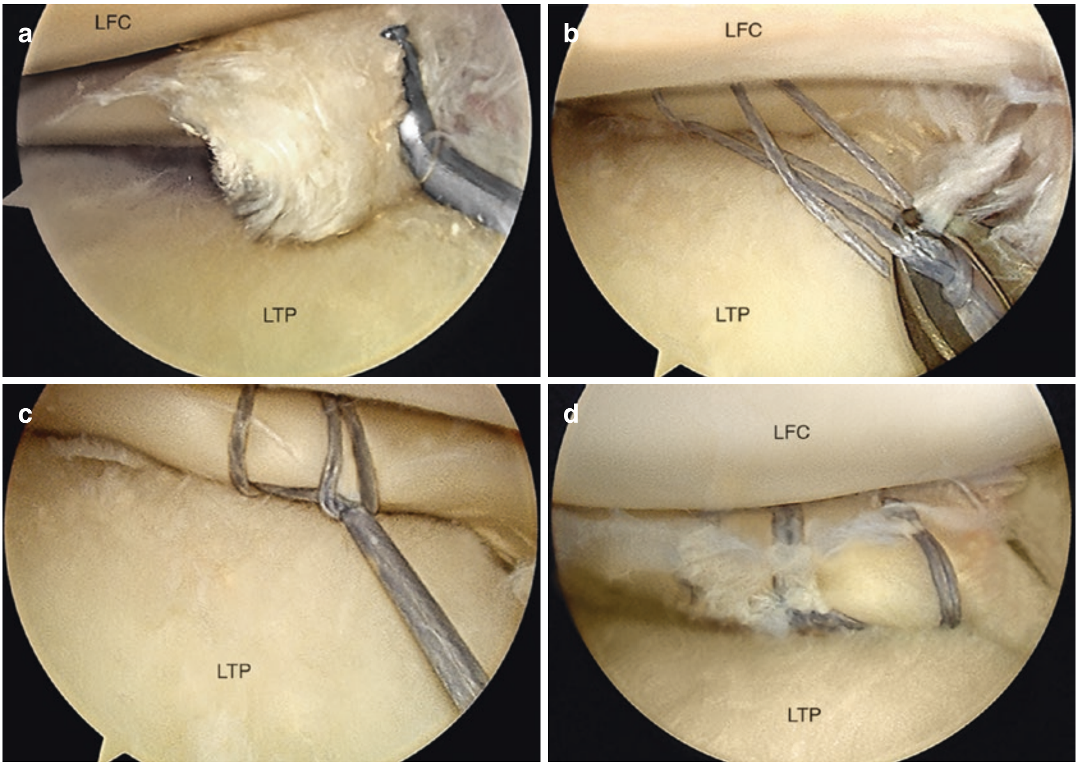


Fig. 1.4 Arthroscopic visualization of a lateral meniscus root tear. (**a**) A double locking loop stitch (NovoStitch, Ceterix) is placed through the meniscus at the tear site (**b**). Three loop stitches were used to achieve a high strength fixation (**c**). Final configuration of the lateral meniscus repair with the meniscus pulled flush to the repair site (**d**) (Reprinted from Noyes and Barber-Westin [115])

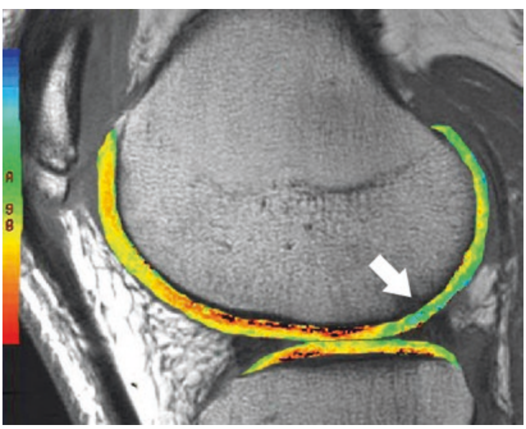


Fig. 1.5 T2 MRI of a 37-year-old male 17 years post-ACL reconstruction and lateral meniscus repair. The patient was asymptomatic with light sports activities. The lateral meniscus repair healed and the ACL reconstruction restored normal stability. Prolongation of T2 values is noted over the posterior margin with adjacent subchondral sclerosis (arrow) (Reprinted from Noyes et al. [155])

dral damage, severe bone bruising, biochemical alterations, patient age, body mass index, failure of the reconstruction to restore normal anteroposterior displacement, complications, and poor quadriceps strength.

- ACL injury causes collagen rupture, joint hemarthrosis, subchondral bone edema, elevated glycosaminoglycan levels, and cell necrosis.
- Bone bruises 80–100% acute ACL rupture, natural history unclear.
- Large severe bone bruises associated with subchondral or osteochondral injuries may persist for years after injury.
- Consider most severe bone injuries part of sequela of post-traumatic OA.
- We have long advocated repair of meniscus tears when appropriate indications met to preserve this vital structure.

References

1. Sanders TL, Maradit Kremers H, Bryan AJ, Larson DR, Dahm DL, Levy BA, Stuart MJ, Krych AJ. Incidence of anterior cruciate ligament tears and reconstruction: a 21-year population-based study. Am J Sports Med. 2016;44(6):1502–7. https://doi.org/10.1177/0363546516629944.
2. Ardern CL, Osterberg A, Sonesson S, Gauffin H, Webster KE, Kvist J. Satisfaction with knee function after primary anterior cruciate ligament reconstruction is associated with self-efficacy, quality of life, and returning to the preinjury physical activity. Arthroscopy. 2016;32(8):1631–1638 e1633. https://doi.org/10.1016/j.arthro.2016.01.035.
3. Ardern CL, Osterberg A, Tagesson S, Gauffin H, Webster KE, Kvist J. The impact of psychological readiness to return to sport and recreational activities after anterior cruciate ligament reconstruction. Br J Sports Med. 2014;48(22):1613–9. https://doi.org/10.1136/bjsports-2014-093842.
4. Filbay SR, Ackerman IN, Russell TG, Crossley KM. Return to sport matters-longer-term quality of life after ACL reconstruction in people with knee difficulties. Scand J Med Sci Sports. 2017;27(5):514–24. https://doi.org/10.1111/sms.12698.
5. Kocher MS, Steadman JR, Briggs K, Zurakowski D, Sterett WI, Hawkins RJ. Determinants of patient satisfaction with outcome after anterior cruciate ligament reconstruction. J Bone Joint Surg. 2002;84-A(9):1560–72.
6. Novaretti JV, Franciozi CE, Forgas A, Sasaki PH, Ingham SJM, Abdalla RJ. Quadriceps strength deficit at 6 months after ACL reconstruction does not predict return to preinjury sports level. Sports Health. 2018;10(3):266–71. https://doi.org/10.1177/1941738118759911.
7. Nwachukwu BU, Voleti PB, Berkanish P, Chang B, Cohn MR, Williams RJ, Allen AA. Return to play and patient satisfaction after ACL reconstruction: study with minimum 2-year follow-up. J Bone Joint Surg. 2017;99(9):720–5. https://doi.org/10.2106/JBJS.16.00958.
8. Sonesson S, Kvist J, Ardern C, Osterberg A, Silbernagel KG. Psychological factors are important to return to pre-injury sport activity after anterior cruciate ligament reconstruction: expect and motivate to satisfy. Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1375–84. https://doi.org/10.1007/s00167-016-4294-8.
9. Lynch AD, Logerstedt DS, Grindem H, Eitzen I, Hicks GE, Axe MJ, Engebretsen L, Risberg MA, Snyder-Mackler L. Consensus criteria for defining 'successful outcome' after ACL injury and reconstruction: a Delaware-Oslo ACL cohort investigation. Br J Sports Med. 2015;49(5):335–42. https://doi.org/10.1136/bjsports-2013-092299.
10. Dingenen B, Gokeler A. Optimization of the return-to-sport paradigm after anterior cruciate ligament reconstruction: a critical step back to move forward. Sports Med. 2017;47(8):1487–500. https://doi.org/10.1007/s40279-017-0674-6.
11. Ardern CL, Taylor NF, Feller JA, Webster KE. Fear of re-injury in people who have returned to sport following anterior cruciate ligament reconstruction surgery. J Sci Med Sport. 2012;15(6):488–95. https://doi.org/10.1016/j.jsams.2012.03.015.
12. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2013;41(7):1549–58. https://doi.org/10.1177/0363546513489284.
13. Ardern CL. Anterior cruciate ligament reconstruction-not exactly a one-way ticket back to the preinjury level: a review of contextual factors affecting return to sport after surgery. Sports Health. 2015;7(3):224–30. https://doi.org/10.1177/1941738115578131.
14. Christino MA, Fantry AJ, Vopat BG. Psychological aspects of recovery following anterior cruciate ligament reconstruction. J Am Acad Orthop Surg. 2015;23(8):501–9. https://doi.org/10.5435/JAAOS-D-14-00173.
15. Ellman MB, Sherman SL, Forsythe B, LaPrade RF, Cole BJ, Bach BR Jr. Return to play following anterior cruciate ligament reconstruction. J Am Acad Orthop Surg. 2015;23(5):283–96. https://doi.org/10.5435/JAAOS-D-13-00183.
16. Everhart JS, Best TM, Flanigan DC. Psychological predictors of anterior cruciate ligament reconstruction outcomes: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2015;23(3):752–62. https://doi.org/10.1007/s00167-013-2699-1.
17. Faltstrom A, Hagglund M, Kvist J. Factors associated with playing football after anterior cruciate ligament reconstruction in female football players. Scand J Med Sci Sports. 2016;26(11):1343–52. https://doi.org/10.1111/sms.12588.
18. Flanigan DC, Everhart JS, Pedroza A, Smith T, Kaeding CC. Fear of reinjury (kinesiophobia) and persistent knee symptoms are common factors for lack of return to sport after anterior cruciate ligament reconstruction. Arthroscopy. 2013;29(8):1322–9. https://doi.org/10.1016/j.arthro.2013.05.015.
19. Garcia GH, Wu HH, Park MJ, Tjoumakaris FP, Tucker BS, Kelly JD, Sennett BJ. Depression symptomatology and anterior cruciate ligament injury: incidence and effect on functional outcome--a prospective cohort study. Am J Sports Med. 2016;44(3):572–9. https://doi.org/10.1177/0363546515612466.
20. Hsu CJ, Meierbachtol A, George SZ, Chmielewski TL. Fear of reinjury in athletes. Sports Health. 2017;9(2):162–7. https://doi.org/10.1177/1941738116666813.
21. Lentz TA, Zeppieri G Jr, George SZ, Tillman SM, Moser MW, Farmer KW, Chmielewski TL. Comparison of physical impairment, functional, and psychosocial measures based on fear of reinjury/lack of confidence and return-to-sport status after ACL

reconstruction. Am J Sports Med. 2015;43(2):345–53. https://doi.org/10.1177/0363546514559707.
22. Podlog L, Heil J, Schulte S. Psychosocial factors in sports injury rehabilitation and return to play. Phys Med Rehabil Clin N Am. 2014;25(4):915–30. https://doi.org/10.1016/j.pmr.2014.06.011.
23. Rodriguez-Roiz JM, Caballero M, Ares O, Sastre S, Lozano L, Popescu D. Return to recreational sports activity after anterior cruciate ligament reconstruction: a one- to six-year follow-up study. Arch Orthop Trauma Surg. 2015;135(8):1117–22. https://doi.org/10.1007/s00402-015-2240-8.
24. Tjong VK, Murnaghan ML, Nyhof-Young JM, Ogilvie-Harris DJ. A qualitative investigation of the decision to return to sport after anterior cruciate ligament reconstruction: to play or not to play. Am J Sports Med. 2014;42(2):336–42. https://doi.org/10.1177/0363546513508762.
25. Webster KE, Nagelli CV, Hewett TE, Feller JA. Factors associated with psychological readiness to return to sport after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2018;46(7):1545–50. https://doi.org/10.1177/0363546518773757.
26. Webster KE, Feller JA, Kimp AJ, Whitehead TS. Low rates of return to preinjury sport after bilateral anterior cruciate ligament reconstruction. Am J Sports Med. 2018;47(2):334–8. https://doi.org/10.1177/0363546518813901.
27. Lentz TA, Zeppieri G Jr, Tillman SM, Indelicato PA, Moser MW, George SZ, Chmielewski TL. Return to preinjury sports participation following anterior cruciate ligament reconstruction: contributions of demographic, knee impairment, and self-report measures. J Orthop Sports Phys Ther. 2012;42(11):893–901. https://doi.org/10.2519/jospt.2012.4077.
28. Rosso F, Bonasia DE, Cottino U, Cambursano S, Dettoni F, Rossi R. Factors affecting subjective and objective outcomes and return to play in anterior cruciate ligament reconstruction: a retrospective cohort study. Joints. 2018;6(1):23–32. https://doi.org/10.1055/s-0038-1636931.
29. Sandon A, Werner S, Forssblad M. Factors associated with returning to football after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2015;23(9):2514–21. https://doi.org/10.1007/s00167-014-3023-4.
30. Baumeister J, Reinecke K, Weiss M. Changed cortical activity after anterior cruciate ligament reconstruction in a joint position paradigm: an EEG study. Scand J Med Sci Sports. 2008;18(4):473–84. https://doi.org/10.1111/j.1600-0838.2007.00702.x.
31. Baumeister J, Reinecke K, Schubert M, Weiss M. Altered electrocortical brain activity after ACL reconstruction during force control. J Orthop Res. 2011;29(9):1383–9. https://doi.org/10.1002/jor.21380.
32. Grooms DR, Page SJ, Nichols-Larsen DS, Chaudhari AM, White SE, Onate JA. Neuroplasticity associated with anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2017;47(3):180–9. https://doi.org/10.2519/jospt.2017.7003.
33. Kapreli E, Athanasopoulos S, Gliatis J, Papathanasiou M, Peeters R, Strimpakos N, Van Hecke P, Gouliamos A, Sunaert S. Anterior cruciate ligament deficiency causes brain plasticity: a functional MRI study. Am J Sports Med. 2009;37(12):2419–26. https://doi.org/10.1177/0363546509343201.
34. Lepley AS, Gribble PA, Thomas AC, Tevald MA, Sohn DH, Pietrosimone BG. Quadriceps neural alterations in anterior cruciate ligament reconstructed patients: a 6-month longitudinal investigation. Scand J Med Sci Sports. 2015;25(6):828–39. https://doi.org/10.1111/sms.12435.
35. Luc-Harkey BA, Harkey MS, Pamukoff DN, Kim RH, Royal TK, Blackburn JT, Spang JT, Pietrosimone B. Greater intracortical inhibition associates with lower quadriceps voluntary activation in individuals with ACL reconstruction. Exp Brain Res. 2017;235(4):1129–37. https://doi.org/10.1007/s00221-017-4877-8.
36. Miao X, Huang H, Hu X, Li D, Yu Y, Ao Y. The characteristics of EEG power spectra changes after ACL rupture. PLoS One. 2017;12(2):e0170455. https://doi.org/10.1371/journal.pone.0170455.
37. Swanik CB. Brains and sprains: the brain's role in noncontact anterior cruciate ligament injuries. J Athl Train. 2015;50(10):1100–2. https://doi.org/10.4085/1062-6050-50.10.08.
38. Bien DP, Dubuque TJ. Considerations for late stage ACL rehabilitation and return to sport to limit re-injury risk and maximize athletic performance. Int J Sports Phys Ther. 2015;10(2):256–71.
39. Grooms D, Appelbaum G, Onate J. Neuroplasticity following anterior cruciate ligament injury: a framework for visual-motor training approaches in rehabilitation. J Orthop Sports Phys Ther. 2015;45(5):381–93. https://doi.org/10.2519/jospt.2015.5549.
40. Ahn JH, Kim JG, Wang JH, Jung CH, Lim HC. Long-term results of anterior cruciate ligament reconstruction using bone-patellar tendon-bone: an analysis of the factors affecting the development of osteoarthritis. Arthroscopy. 2012;28(8):1114–23. https://doi.org/10.1016/j.arthro.2011.12.019.
41. Barenius B, Ponzer S, Shalabi A, Bujak R, Norlen L, Eriksson K. Increased risk of osteoarthritis after anterior cruciate ligament reconstruction: a 14-year follow-up study of a randomized controlled trial. Am J Sports Med. 2014;42(5):1049–57. https://doi.org/10.1177/0363546514526139.
42. Cantin O, Lustig S, Rongieras F, Saragaglia D, Lefevre N, Graveleau N, Hulet C. Outcome of cartilage at 12 years of follow-up after anterior cruciate ligament reconstruction. OTSR. 2016;102(7):857–61. https://doi.org/10.1016/j.otsr.2016.06.011.
43. Claes S, Hermie L, Verdonk R, Bellemans J, Verdonk P. Is osteoarthritis an inevitable consequence of anterior cruciate ligament reconstruction? A meta-analysis. Knee Surg Sports Traumatol

Arthrosc. 2013;21(9):1967–76. https://doi.org/10.1007/s00167-012-2251-8.
44. Devitt BM, Bell SW, Webster KE, Feller JA, Whitehead TS. Surgical treatments of cartilage defects of the knee: systematic review of randomised controlled trials. Knee. 2017;24(3):508–17. https://doi.org/10.1016/j.knee.2016.12.002.
45. Gerhard P, Bolt R, Duck K, Mayer R, Friederich NF, Hirschmann MT. Long-term results of arthroscopically assisted anatomical single-bundle anterior cruciate ligament reconstruction using patellar tendon autograft: are there any predictors for the development of osteoarthritis? Knee Surg Sports Traumatol Arthrosc. 2013;21(4):957–64. https://doi.org/10.1007/s00167-012-2001-y.
46. Keays SL, Newcombe PA, Bullock-Saxton JE, Bullock MI, Keays AC. Factors involved in the development of osteoarthritis after anterior cruciate ligament surgery. Am J Sports Med. 2010;38(3):455–63. https://doi.org/10.1177/0363546509350914.
47. Li RT, Lorenz S, Xu Y, Harner CD, Fu FH, Irrgang JJ. Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. Am J Sports Med. 2011;39(12):2595–603. https://doi.org/10.1177/0363546511424720.
48. Shelbourne KD, Gray T. Minimum 10-year results after anterior cruciate ligament reconstruction: how the loss of normal knee motion compounds other factors related to the development of osteoarthritis after surgery. Am J Sports Med. 2009;37(3):471–80. https://doi.org/10.1177/0363546508326709.
49. Beynnon BD, Uh BS, Johnson RJ, Abate JA, Nichols CE, Fleming BC, Poole AR, Roos H. Rehabilitation after anterior cruciate ligament reconstruction. A prospective, randomized, double-blind comparison of programs administered over 2 different time periods. Am J Sports Med. 2005;33(3):347–59.
50. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, part I. Am J Sports Med. 2005;33(10):1579–602.
51. Hui C, Salmon LJ, Kok A, Maeno S, Linklater J, Pinczewski LA. Fifteen-year outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft for "isolated" anterior cruciate ligament tear. Am J Sports Med. 2011;39(1):89–98. https://doi.org/10.1177/0363546510379975.
52. Myklebust G, Bahr R. Return to play guidelines after anterior cruciate ligament surgery. Br J Sports Med. 2005;39(3):127–31. https://doi.org/10.1136/bjsm.2004.010900.
53. Smith MV, Nepple JJ, Wright RW, Matava MJ, Brophy RH. Knee osteoarthritis is associated with previous meniscus and anterior cruciate ligament surgery among elite college American football athletes. Sports Health. 2017;9(3):247–51. https://doi.org/10.1177/1941738116683146.
54. Theologis AA, Kuo D, Cheng J, Bolbos RI, Carballido-Gamio J, Ma CB, Li X. Evaluation of bone bruises and associated cartilage in anterior cruciate ligament-injured and -reconstructed knees using quantitative t(1rho) magnetic resonance imaging: 1-year cohort study. Arthroscopy. 2011;27(1):65–76. https://doi.org/10.1016/j.arthro.2010.06.026.
55. Weinstein AM, Rome BN, Reichmann WM, Collins JE, Burbine SA, Thornhill TS, Wright J, Katz JN, Losina E. Estimating the burden of total knee replacement in the United States. J Bone Joint Surg. 2013;95(5):385–92. https://doi.org/10.2106/JBJS.L.00206.
56. Makhni EC, Padaki AS, Petridis PD, Steinhaus ME, Ahmad CS, Cole BJ, Bach BR Jr. High variability in outcome reporting patterns in high-impact ACL literature. J Bone Joint Surg. 2015;97(18):1529–42. https://doi.org/10.2106/JBJS.O.00155.
57. Ardern CL, Sonesson S, Forssblad M, Kvist J. Comparison of patient-reported outcomes among those who chose ACL reconstruction or non-surgical treatment. Scand J Med Sci Sports. 2017;27(5):535–44. https://doi.org/10.1111/sms.12707.
58. Salmon LJ, Heath E, Akrawi H, Roe JP, Linklater J, Pinczewski LA. 20-year outcomes of anterior cruciate ligament reconstruction with hamstring tendon autograft: the catastrophic effect of age and posterior tibial slope. Am J Sports Med. 2018;46(3):531–43. https://doi.org/10.1177/0363546517741497.
59. Morgan MD, Salmon LJ, Waller A, Roe JP, Pinczewski LA. Fifteen-year survival of endoscopic anterior cruciate ligament reconstruction in patients aged 18 years and younger. Am J Sports Med. 2016;44(2):384–92. https://doi.org/10.1177/0363546515623032.
60. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med. 2009;37(2):246–51.
61. Takazawa Y, Ikeda H, Saita Y, Kawasaki T, Ishijima M, Nagayama M, Kaneko H, Kaneko K. Return to play of rugby players after anterior cruciate ligament reconstruction using hamstring autograft: return to sports and graft failure according to age. Arthroscopy. 2017;33(1):181–9. https://doi.org/10.1016/j.arthro.2016.06.009.
62. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Am J Sports Med. 2016;44(7):1861–76. https://doi.org/10.1177/0363546515621554.
63. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med. 2016;50(13):804–8. https://doi.org/10.1136/bjsports-2016-096031.
64. Webster KE, Feller JA, Leigh WB, Richmond AK. Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. Am J

Sports Med. 2014;42(3):641–7. https://doi.org/10.1177/0363546513517540.
65. Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, Consortium M, Spindler KP. Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: prospective analysis of 2488 primary ACL reconstructions from the moon cohort. Am J Sports Med. 2015;43(7):1583–90. https://doi.org/10.1177/0363546515578836.
66. Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. Br J Sports Med. 2016;50(15):946–51. https://doi.org/10.1136/bjsports-2015-095908.
67. Kamath GV, Murphy T, Creighton RA, Viradia N, Taft TN, Spang JT. Anterior cruciate ligament injury, return to play, and reinjury in the elite collegiate athlete: analysis of an NCAA Division I Cohort. Am J Sports Med. 2014;42(7):1638–43. https://doi.org/10.1177/0363546514524164.
68. Lefevre N, Klouche S, Mirouse G, Herman S, Gerometta A, Bohu Y. Return to sport after primary and revision anterior cruciate ligament reconstruction: a prospective comparative study of 552 patients from the FAST Cohort. Am J Sports Med. 2017;45(1):34–41. https://doi.org/10.1177/0363546516660075.
69. Faltstrom A, Hagglund M, Magnusson H, Forssblad M, Kvist J. Predictors for additional anterior cruciate ligament reconstruction: data from the Swedish national ACL register. Knee Surg Sports Traumatol Arthrosc. 2016;24(3):885–94. https://doi.org/10.1007/s00167-014-3406-6.
70. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Sports participation 2 years after anterior cruciate ligament reconstruction in athletes who had not returned to sport at 1 year: a prospective follow-up of physical function and psychological factors in 122 athletes. Am J Sports Med. 2015;43(4):848–56. https://doi.org/10.1177/0363546514563282.
71. Myklebust G, Holm I, Maehlum S, Engebretsen L, Bahr R. Clinical, functional, and radiologic outcome in team handball players 6 to 11 years after anterior cruciate ligament injury: a follow-up study. Am J Sports Med. 2003;31(6):981–9.
72. Mohtadi N, Chan D, Barber R, Paolucci EO. Reruptures, reinjuries, and revisions at a minimum 2-year follow-up: a randomized clinical trial comparing 3 graft types for ACL reconstruction. Clin J Sport Med. 2016;26(2):96–107. https://doi.org/10.1097/JSM.0000000000000209.
73. Park SY, Oh H, Park S, Lee JH, Lee SH, Yoon KH. Factors predicting hamstring tendon autograft diameters and resulting failure rates after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2013;21(5):1111–8. https://doi.org/10.1007/s00167-012-2085-4.
74. Thompson SM, Salmon LJ, Waller A, Linklater J, Roe JP, Pinczewski LA. Twenty-year outcome of a longitudinal prospective evaluation of isolated endoscopic anterior cruciate ligament reconstruction with patellar tendon or hamstring autograft. Am J Sports Med. 2016;44(12):3083–94. https://doi.org/10.1177/0363546516658041.
75. Pinczewski LA, Lyman J, Salmon LJ, Russell VJ, Roe J, Linklater J. A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: a controlled, prospective trial. Am J Sports Med. 2007;35(4):564–74.
76. Hettrich CM, Dunn WR, Reinke EK, Group M, Spindler KP. The rate of subsequent surgery and predictors after anterior cruciate ligament reconstruction: two- and 6-year follow-up results from a multicenter cohort. Am J Sports Med. 2013;41(7):1534–40. https://doi.org/10.1177/0363546513490277.
77. Schlumberger M, Schuster P, Schulz M, Immendorfer M, Mayer P, Bartholoma J, Richter J. Traumatic graft rupture after primary and revision anterior cruciate ligament reconstruction: retrospective analysis of incidence and risk factors in 2915 cases. Knee Surg Sports Traumatol Arthrosc. 2015;25(5):1535–41. https://doi.org/10.1007/s00167-015-3699-0.
78. Webster KE, Feller JA. Exploring the high reinjury rate in younger patients undergoing anterior cruciate ligament reconstruction. Am J Sports Med. 2016;44(11):2827–32. https://doi.org/10.1177/0363546516651845.
79. Persson A, Fjeldsgaard K, Gjertsen JE, Kjellsen AB, Engebretsen L, Hole RM, Fevang JM. Increased risk of revision with hamstring tendon grafts compared with patellar tendon grafts after anterior cruciate ligament reconstruction: a study of 12,643 patients from the Norwegian Cruciate Ligament Registry, 2004-2012. Am J Sports Med. 2014;42(2):285–91. https://doi.org/10.1177/0363546513511419.
80. Kamien PM, Hydrick JM, Replogle WH, Go LT, Barrett GR. Age, graft size, and Tegner activity level as predictors of failure in anterior cruciate ligament reconstruction with hamstring autograft. Am J Sports Med. 2013;41(8):1808–12. https://doi.org/10.1177/0363546513493896.
81. Maletis GB, Inacio MC, Funahashi TT. Risk factors associated with revision and contralateral anterior cruciate ligament reconstructions in the Kaiser Permanente ACLR registry. Am J Sports Med. 2015;43(3):641–7. https://doi.org/10.1177/0363546514561745.
82. Leys T, Salmon L, Waller A, Linklater J, Pinczewski L. Clinical results and risk factors for reinjury 15 years after anterior cruciate ligament reconstruction: a prospective study of hamstring and patellar tendon grafts. Am J Sports Med. 2012;40(3):595–605. https://doi.org/10.1177/0363546511430375.
83. Dekker TJ, Godin JA, Dale KM, Garrett WE, Taylor DC, Riboh JC. Return to sport after pediatric anterior cruciate ligament reconstruction and its effect

on subsequent anterior cruciate ligament injury. J Bone Joint Surg. 2017;99(11):897–904. https://doi.org/10.2106/JBJS.16.00758.
84. Andernord D, Desai N, Bjornsson H, Ylander M, Karlsson J, Samuelsson K. Patient predictors of early revision surgery after anterior cruciate ligament reconstruction: a cohort study of 16,930 patients with 2-year follow-up. Am J Sports Med. 2015;43(1):121–7. https://doi.org/10.1177/0363546514552788.
85. Anand BS, Feller JA, Richmond AK, Webster KE. Return-to-sport outcomes after revision anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2016;44(3):580–4. https://doi.org/10.1177/0363546515618381.
86. Kamath GV, Redfern JC, Greis PE, Burks RT. Revision anterior cruciate ligament reconstruction. Am J Sports Med. 2011;39(1):199–217. https://doi.org/10.1177/0363546510370929.
87. Marchant BG, Noyes FR, Barber-Westin SD, Fleckenstein C. Prevalence of nonanatomical graft placement in a series of failed anterior cruciate ligament reconstructions. Am J Sports Med. 2010;38(10):1987–96. https://doi.org/10.1177/0363546510372797.
88. MARS. Effect of graft choice on the outcome of revision anterior cruciate ligament reconstruction in the multicenter ACL Revision Study (MARS) Cohort. Am J Sports Med. 2014;42(10):2301–10. https://doi.org/10.1177/0363546514549005.
89. Noyes FR, Barber-Westin SD. Revision anterior cruciate ligament reconstruction: report of 11-year experience and results in 114 consecutive patients. Instr Course Lect. 2001;50:451–61.
90. Trojani C, Sbihi A, Djian P, Potel JF, Hulet C, Jouve F, Bussiere C, Ehkirch FP, Burdin G, Dubrana F, Beaufils P, Franceschi JP, Chassaing V, Colombet P, Neyret P. Causes for failure of ACL reconstruction and influence of meniscectomies after revision. Knee Surg Sports Traumatol Arthrosc. 2011;19(2):196–201. https://doi.org/10.1007/s00167-010-1201-6.
91. Andernord D, Desai N, Bjornsson H, Gillen S, Karlsson J, Samuelsson K. Predictors of contralateral anterior cruciate ligament reconstruction: a cohort study of 9061 patients with 5-year follow-up. Am J Sports Med. 2015;43(2):295–302. https://doi.org/10.1177/0363546514557245.
92. Faltstrom A, Kvist J, Gauffin H, Hagglund M. Female soccer players with anterior cruciate ligament reconstruction have a higher risk of new knee injuries and quit soccer to a higher degree than knee-healthy controls. Am J Sports Med. 2019;47(1):31–40. https://doi.org/10.1177/0363546518808006.
93. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. Am J Sports Med. 2011;39(3):538–43. https://doi.org/10.1177/0363546510384798.
94. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med. 2014;48(21):1543–52. https://doi.org/10.1136/bjsports-2013-093398.
95. Hamrin Senorski E, Samuelsson K, Thomee C, Beischer S, Karlsson J, Thomee R. Return to knee-strenuous sport after anterior cruciate ligament reconstruction: a report from a rehabilitation outcome registry of patient characteristics. Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1364–74. https://doi.org/10.1007/s00167-016-4280-1.
96. Nawasreh Z, Logerstedt D, Cummer K, Axe MJ, Risberg MA, Snyder-Mackler L. Do patients failing return-to-activity criteria at 6 months after anterior cruciate ligament reconstruction continue demonstrating deficits at 2 years? Am J Sports Med. 2017;45(5):1037–48. https://doi.org/10.1177/0363546516680619.
97. Kay J, Memon M, Marx RG, Peterson D, Simunovic N, Ayeni OR. Over 90 % of children and adolescents return to sport after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Knee Surg Sports Traumatol Arthrosc. 2018;26(4):1019–36. https://doi.org/10.1007/s00167-018-4830-9.
98. Shelbourne KD, Benner RW, Gray T. Results of anterior cruciate ligament reconstruction with patellar tendon autografts: objective factors associated with the development of osteoarthritis at 20 to 33 years after surgery. Am J Sports Med. 2017;45(12):2730–8. https://doi.org/10.1177/0363546517718827.
99. Oiestad BE, Holm I, Engebretsen L, Aune AK, Gunderson R, Risberg MA. The prevalence of patellofemoral osteoarthritis 12 years after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2013;21(4):942–9. https://doi.org/10.1007/s00167-012-2161-9.
100. Holm I, Oiestad BE, Risberg MA, Gunderson R, Aune AK. No differences in prevalence of osteoarthritis or function after open versus endoscopic technique for anterior cruciate ligament reconstruction: 12-year follow-up report of a randomized controlled trial. Am J Sports Med. 2012;40(11):2492–8. https://doi.org/10.1177/0363546512458766.
101. Murray JR, Lindh AM, Hogan NA, Trezies AJ, Hutchinson JW, Parish E, Read JW, Cross MV. Does anterior cruciate ligament reconstruction lead to degenerative disease? Thirteen-year results after bone-patellar tendon-bone autograft. Am J Sports Med. 2012;40(2):404–13. https://doi.org/10.1177/0363546511428580.
102. Pernin J, Verdonk P, Si Selmi TA, Massin P, Neyret P. Long-term follow-up of 24.5 years after intra-articular anterior cruciate ligament reconstruction with lateral extra-articular augmentation. Am J Sports Med. 2010;38(6):1094–102. https://doi.org/10.1177/0363546509361018.

103. Inderhaug E, Strand T, Fischer-Bredenbeck C, Solheim E. Long-term results after reconstruction of the ACL with hamstrings autograft and transtibial femoral drilling. Knee Surg Sports Traumatol Arthrosc. 2013;21(9):2004–10. https://doi.org/10.1007/s00167-012-2330-x.
104. Struewer J, Ziring E, Frangen TM, Efe T, Meissner S, Buecking B, Bliemel C, Ishaque B. Clinical outcome and prevalence of osteoarthritis after isolated anterior cruciate ligament reconstruction using hamstring graft: follow-up after two and ten years. Int Orthop. 2013;37(2):271–7. https://doi.org/10.1007/s00264-012-1653-z.
105. Streich NA, Reichenbacher S, Barie A, Buchner M, Schmitt H. Long-term outcome of anterior cruciate ligament reconstruction with an autologous four-strand semitendinosus tendon autograft. Int Orthop. 2013;37(2):279–84. https://doi.org/10.1007/s00264-012-1757-5.
106. Janssen RP, du Mee AW, van Valkenburg J, Sala HA, Tseng CM. Anterior cruciate ligament reconstruction with 4-strand hamstring autograft and accelerated rehabilitation: a 10-year prospective study on clinical results, knee osteoarthritis and its predictors. Knee Surg Sports Traumatol Arthrosc. 2013;21(9):1977–88. https://doi.org/10.1007/s00167-012-2234-9.
107. Bjornsson H, Samuelsson K, Sundemo D, Desai N, Sernert N, Rostgard-Christensen L, Karlsson J, Kartus J. A randomized controlled trial with mean 16-year follow-up comparing hamstring and patellar tendon autografts in anterior cruciate ligament reconstruction. Am J Sports Med. 2016;44(9):2304–13. https://doi.org/10.1177/0363546516646378.
108. Sanders TL, Kremers HM, Bryan AJ, Fruth KM, Larson DR, Pareek A, Levy BA, Stuart MJ, Dahm DL, Krych AJ. Is anterior cruciate ligament reconstruction effective in preventing secondary meniscal tears and osteoarthritis? Am J Sports Med. 2016;44(7):1699–707. https://doi.org/10.1177/0363546516634325.
109. Ferretti A, Monaco E, Ponzo A, Basiglini L, Iorio R, Caperna L, Conteduca F. Combined intra-articular and extra-articular reconstruction in anterior cruciate ligament-deficient knee: 25 years later. Arthroscopy. 2016;32(10):2039–47. https://doi.org/10.1016/j.arthro.2016.02.006.
110. Hanypsiak BT, Spindler KP, Rothrock CR, Calabrese GJ, Richmond B, Herrenbruck TM, Parker RD. Twelve-year follow-up on anterior cruciate ligament reconstruction: long-term outcomes of prospectively studied osseous and articular injuries. Am J Sports Med. 2008;36(4):671–7.
111. Hoffelner T, Resch H, Moroder P, Atzwanger J, Wiplinger M, Hitzl W, Tauber M. No increased occurrence of osteoarthritis after anterior cruciate ligament reconstruction after isolated anterior cruciate ligament injury in athletes. Arthroscopy. 2012;28(4):517–25. https://doi.org/10.1016/j.arthro.2011.09.014.
112. Kessler MA, Behrend H, Henz S, Stutz G, Rukavina A, Kuster MS. Function, osteoarthritis and activity after ACL-rupture: 11 years follow-up results of conservative versus reconstructive treatment. Knee Surg Sports Traumatol Arthrosc. 2008;16(5):442–8.
113. Thompson S, Salmon L, Waller A, Linklater J, Roe J, Pinczewski L. Twenty-year outcomes of a longitudinal prospective evaluation of isolated endoscopic anterior cruciate ligament reconstruction with patellar tendon autografts. Am J Sports Med. 2015;43(9):2164–74. https://doi.org/10.1177/0363546515591263.
114. Wipfler B, Donner S, Zechmann CM, Springer J, Siebold R, Paessler HH. Anterior cruciate ligament reconstruction using patellar tendon versus hamstring tendon: a prospective comparative study with 9-year follow-up. Arthroscopy. 2011;27(5):653–65. https://doi.org/10.1016/j.arthro.2011.01.015.
115. Noyes FR, Barber-Westin SD. Meniscus tears: diagnosis, surgical techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 677–718.
116. Andreisek G, White LM, Sussman MS, Kunz M, Hurtig M, Weller I, Essue J, Marks P, Eckstein F. Quantitative MR imaging evaluation of the cartilage thickness and subchondral bone area in patients with ACL-reconstructions 7 years after surgery. Osteoarthr Cartil. 2009;17(7):871–8. https://doi.org/10.1016/j.joca.2008.05.024.
117. Culvenor AG, Collins NJ, Guermazi A, Cook JL, Vicenzino B, Khan KM, Beck N, van Leeuwen J, Crossley KM. Early knee osteoarthritis is evident one year following anterior cruciate ligament reconstruction: a magnetic resonance imaging evaluation. Arthritis Rheumatol. 2015;67(4):946–55. https://doi.org/10.1002/art.39005.
118. Hart AJ, Buscombe J, Malone A, Dowd GS. Assessment of osteoarthritis after reconstruction of the anterior cruciate ligament: a study using single-photon emission computed tomography at ten years. J Bone Joint Surg. 2005;87(11):1483–7.
119. Kellgren JH, Lawrence JS. Radiological assessment of osteo-arthrosis. Ann Rheum Dis. 1957;16(4):494–502.
120. Irrgang JJ, Snyder-Mackler L, Wainner RS, Fu FH, Harner CD. Development of a patient-reported measure of function of the knee. J Bone Joint Surg. 1998;80(8):1132–45.
121. Ait Si Selmi T, Fithian D, Neyret P. The evolution of osteoarthritis in 103 patients with ACL reconstruction at 17 years follow-up. Knee. 2006;13(5):353–8. https://doi.org/10.1016/j.knee.2006.02.014.
122. Drogset JO, Grontvedt T, Robak OR, Molster A, Viset AT, Engebretsen L. A sixteen-year follow-up of three operative techniques for the treatment of acute ruptures of the anterior cruciate ligament. J Bone Joint Surg Am. 2006;88(5):944–52.

123. Mihelic R, Jurdana H, Jotanovic Z, Madjarevic T, Tudor A. Long-term results of anterior cruciate ligament reconstruction: a comparison with non-operative treatment with a follow-up of 17-20 years. Int Orthop. 2011;35(7):1093–7. https://doi.org/10.1007/s00264-011-1206-x.
124. Nakata K, Shino K, Horibe S, Tanaka Y, Toritsuka Y, Nakamura N, Koyanagi M, Yoshikawa H. Arthroscopic anterior cruciate ligament reconstruction using fresh-frozen bone plug-free allogeneic tendons: 10-year follow-up. Arthroscopy. 2008;24(3):285–91.
125. Salmon LJ, Russell VJ, Refshauge K, Kader D, Connolly C, Linklater J, Pinczewski LA. Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. Am J Sports Med. 2006;34(5):721–32.
126. Noyes FR, Barber-Westin SD. Treatment of meniscus tears during anterior cruciate ligament reconstruction. Arthroscopy. 2012;28(1):123–30. https://doi.org/10.1016/j.arthro.2011.08.292.
127. Bisson LJ, Kluczynski MA, Hagstrom LS, Marzo JM. A prospective study of the association between bone contusion and intra-articular injuries associated with acute anterior cruciate ligament tear. Am J Sports Med. 2013;41(8):1801–7. https://doi.org/10.1177/0363546513490649.
128. Dunn WR, Spindler KP, Amendola A, Andrish JT, Kaeding CC, Marx RG, McCarty EC, Parker RD, Harrell FE Jr, An AQ, Wright RW, Brophy RH, Matava MJ, Flanigan DC, Huston LJ, Jones MH, Wolcott ML, Vidal AF, Wolf BR. Which preoperative factors, including bone bruise, are associated with knee pain/symptoms at index anterior cruciate ligament reconstruction (ACLR)? A Multicenter Orthopaedic Outcomes Network (MOON) ACLR Cohort Study. Am J Sports Med. 2010;38(9):1778–87. https://doi.org/10.1177/0363546510370279.
129. Nishimori M, Deie M, Adachi N, Kanaya A, Nakamae A, Motoyama M, Ochi M. Articular cartilage injury of the posterior lateral tibial plateau associated with acute anterior cruciate ligament injury. Knee Surg Sports Traumatol Arthrosc. 2008;16(3):270–4. https://doi.org/10.1007/s00167-007-0458-x.
130. Papalia R, Torre G, Vasta S, Zampogna B, Pedersen DR, Denaro V, Amendola A. Bone bruises in anterior cruciate ligament injured knee and long-term outcomes. A review of the evidence. Open Access J Sports Med. 2015;6:37–48. https://doi.org/10.2147/OAJSM.S75345.
131. Potter HG, Jain SK, Ma Y, Black BR, Fung S, Lyman S. Cartilage injury after acute, isolated anterior cruciate ligament tear: immediate and longitudinal effect with clinical/MRI follow-up. Am J Sports Med. 2012;40(2):276–85. https://doi.org/10.1177/0363546511423380.
132. Yoon JP, Chang CB, Yoo JH, Kim SJ, Choi JY, Choi JA, Seong SC, Kim TK. Correlation of magnetic resonance imaging findings with the chronicity of an anterior cruciate ligament tear. J Bone Joint Surg. 2010;92(2):353–60. https://doi.org/10.2106/JBJS.I.00031.
133. Yoon KH, Yoo JH, Kim KI. Bone contusion and associated meniscal and medial collateral ligament injury in patients with anterior cruciate ligament rupture. J Bone Joint Surg. 2011;93(16):1510–8. https://doi.org/10.2106/JBJS.J.01320.
134. Frobell RB. Change in cartilage thickness, posttraumatic bone marrow lesions, and joint fluid volumes after acute ACL disruption: a two-year prospective MRI study of sixty-one subjects. J Bone Joint Surg. 2011;93(12):1096–103. https://doi.org/10.2106/JBJS.J.00929.
135. Amano K, Huebner JL, Stabler TV, Tanaka M, McCulloch CE, Lobach I, Lane NE, Kraus VB, Ma CB, Li X. Synovial fluid profile at the time of anterior cruciate ligament reconstruction and its association with cartilage matrix composition 3 years after surgery. Am J Sports Med. 2018;46(4):890–9. https://doi.org/10.1177/0363546517749834.
136. Bigoni M, Sacerdote P, Turati M, Franchi S, Gandolla M, Gaddi D, Moretti S, Munegato D, Augusti CA, Bresciani E, Omeljaniuk RJ, Locatelli V, Torsello A. Acute and late changes in intraarticular cytokine levels following anterior cruciate ligament injury. J Orthop Res. 2013;31(2):315–21. https://doi.org/10.1002/jor.22208.
137. Cuellar VG, Cuellar JM, Golish SR, Yeomans DC, Scuderi GJ. Cytokine profiling in acute anterior cruciate ligament injury. Arthroscopy. 2010;26(10):1296–301. https://doi.org/10.1016/j.arthro.2010.02.011.
138. Elsaid KA, Fleming BC, Oksendahl HL, Machan JT, Fadale PD, Hulstyn MJ, Shalvoy R, Jay GD. Decreased lubricin concentrations and markers of joint inflammation in the synovial fluid of patients with anterior cruciate ligament injury. Arthritis Rheum. 2008;58(6):1707–15. https://doi.org/10.1002/art.23495.
139. Fang C, Johnson D, Leslie MP, Carlson CS, Robbins M, Di Cesare PE. Tissue distribution and measurement of cartilage oligomeric matrix protein in patients with magnetic resonance imaging-detected bone bruises after acute anterior cruciate ligament tears. J Orthop Res. 2001;19(4):634–41. https://doi.org/10.1016/S0736-0266(00)00039-5.
140. Higuchi H, Shirakura K, Kimura M, Terauchi M, Shinozaki T, Watanabe H, Takagishi K. Changes in biochemical parameters after anterior cruciate ligament injury. Int Orthop. 2006;30(1):43–7. https://doi.org/10.1007/s00264-005-0023-5.
141. Irie K, Tomatsu T. Atrophy of semitendinosus and gracilis and flexor mechanism function after hamstring tendon harvest for anterior cruciate ligament reconstruction. Orthopedics. 2002;25(5):491–5.
142. Lee JH, Ort T, Ma K, Picha K, Carton J, Marsters PA, Lohmander LS, Baribaud F, Song XY, Blake S. Resistin is elevated following traumatic joint injury and causes matrix degradation and release of inflammatory cytokines from articular cartilage

in vitro. Osteoarthr Cartil. 2009;17(5):613–20. https://doi.org/10.1016/j.joca.2008.08.007.
143. Li H, Chen C, Chen S. Posttraumatic knee osteoarthritis following anterior cruciate ligament injury: potential biochemical mediators of degenerative alteration and specific biochemical markers. Biomed Rep. 2015;3(2):147–51. https://doi.org/10.3892/br.2014.404.
144. Lohmander LS, Atley LM, Pietka TA, Eyre DR. The release of crosslinked peptides from type II collagen into human synovial fluid is increased soon after joint injury and in osteoarthritis. Arthritis Rheum. 2003;48(11):3130–9. https://doi.org/10.1002/art.11326.
145. Lotz MK, Kraus VB. New developments in osteoarthritis. Posttraumatic osteoarthritis: pathogenesis and pharmacological treatment options. Arthritis Res Ther. 2010;12(3):211. https://doi.org/10.1186/ar3046.
146. Marks PH, Donaldson ML. Inflammatory cytokine profiles associated with chondral damage in the anterior cruciate ligament-deficient knee. Arthroscopy. 2005;21(11):1342–7. https://doi.org/10.1016/j.arthro.2005.08.034.
147. Mutsuzaki H, Sakane M, Honda K, Ikeda K, Hattori S, Ochiai N. Cell death and cell proliferation in cartilage layers in human anterior cruciate ligament tibial insertions after rupture. Connect Tissue Res. 2010;51(4):282–8. https://doi.org/10.3109/03008200903318303.
148. Papathanasiou I, Michalitsis S, Hantes ME, Vlychou M, Anastasopoulou L, Malizos KN, Tsezou A. Molecular changes indicative of cartilage degeneration and osteoarthritis development in patients with anterior cruciate ligament injury. BMC Musculoskelet Disord. 2016;17:21. https://doi.org/10.1186/s12891-016-0871-8.
149. Struglics A, Larsson S, Kumahashi N, Frobell R, Lohmander LS. Changes in cytokines and aggrecan ARGS neoepitope in synovial fluid and serum and in c-terminal crosslinking telopeptide of type II collagen and n-terminal crosslinking telopeptide of type I collagen in urine over five years after anterior cruciate ligament rupture: an exploratory analysis in the knee anterior cruciate ligament, nonsurgical versus surgical treatment trial. Arthritis Rheumatol. 2015;67(7):1816–25. https://doi.org/10.1002/art.39146.
150. Tiderius CJ, Olsson LE, Nyquist F, Dahlberg L. Cartilage glycosaminoglycan loss in the acute phase after an anterior cruciate ligament injury: delayed gadolinium-enhanced magnetic resonance imaging of cartilage and synovial fluid analysis. Arthritis Rheum. 2005;52(1):120–7. https://doi.org/10.1002/art.20795.
151. Noyes FR, Barber-Westin SD. Risks of future joint arthritis and reinjury after ACL reconstruction. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete: causes, impacts, and conditioning programs. 2nd ed; 2018. p. 67–93.
152. Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscal tears extending into the avascular zone in patients younger than twenty years of age. Am J Sports Med. 2002;30(4):589–600.
153. Noyes FR, Barber-Westin SD. Meniscus tears: diagnosis, repair techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 677–718. https://doi.org/10.1016/b978-0-323-32903-3.00023-8.
154. Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscus tears extending into the avascular zone with or without anterior cruciate ligament reconstruction in patients 40 years of age and older. Arthroscopy. 2000;16(8):822–9. https://doi.org/10.1053/jars.2000.19434.
155. Noyes FR, Chen RC, Barber-Westin SD, Potter HG. Greater than 10-year results of red-white longitudinal meniscal repairs in patients 20 years of age or younger. Am J Sports Med. 2011;39(5):1008–17. https://doi.org/10.1177/0363546510392014.
156. Rubman MH, Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscal tears that extend into the avascular zone. A review of 198 single and complex tears. Am J Sports Med. 1998;26(1):87–95.

Common Symptom, Psychological, and Psychosocial Barriers to Return to Sport

2

Sue Barber-Westin and Frank R. Noyes

2.1 Common Physical Barriers

Anterior cruciate ligament (ACL) reconstruction is most commonly performed in younger active individuals whose main goal is to return to full unrestricted athletic activities without lingering knee symptoms or functional limitations. In the long term, the expectation of the outcome of ACL reconstruction is the continuation of an active lifestyle as well as the prevention of further knee injuries and premature osteoarthritis (OA). High patient satisfaction and quality of life scores are directly associated with return to an active lifestyle. Unfortunately, there are many barriers that prevent or delay return to sports (RTS) including psychological factors, psychosocial issues, inadequate rehabilitation, and surgical complications. Knee pain, swelling, and/or instability represent the most common symptom obstacles to RTS (Table 2.1) [1–11].

Flanigan et al. [2] conducted a telephone interview study of 135 patients to determine the most common reasons for failure to RTS 1–2 years after ACL reconstruction. In a group of 73 patients that were unable to RTS, persistent knee symptoms were the most frequently cited reason, occurring in 68% (Fig. 2.1), followed by fear of reinjury, documented in 52%. Pain was the most frequent symptom, followed by swelling, stiffness, and instability (Fig. 2.2).

Sandon et al. [10] in a survey study of 205 soccer players followed a mean of 3.2 years after ACL reconstruction reported that 46% failed to return to soccer. Significant predictors for failure to return included pain with physical activity ($P = 0.002$), female gender ($P < 0.05$), and articular cartilage injury ($P = 0.01$). There was a significant difference between those who returned and those who did not return to soccer in the percent of patients who experienced pain (39% and 61%, respectively, $P < 0.01$), stiffness (43% and 57%, respectively, $P = 0.01$), and instability (22% and 39%, respectively, $P < 0.05$, Fig. 2.3).

Lefevre et al. [5] followed 497 primary ACL reconstruction and 55 ACL revision patients for 1 year postoperatively and reported that 36% and 51%, respectively, had not resumed their usual sport. The majority of these patients reported knee symptoms of either pain, instability, or stiffness as the reason (Fig. 2.4). Lentz et al. [6] documented demographic, physical impairment, and psychosocial factors that prohibited RTS in a cohort of 94 patients 1 year after ACL reconstruction. Forty-five percent had not returned to preinjury activity levels, and of these, 40% reported that the primary reason was either pain, swelling, instability, or weakness. A group of 62 patients who underwent ACL reconstruction were fol-

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_2

Table 2.1 Symptoms that prevented patients from returning to preinjury sports activity levels after ACL reconstruction

Study	No. knees, mean follow-up	ACL graft	Returned to preinjury activity level?		Patients that did not return to preinjury sports activity level					
			Yes	No	Any symptom reported	Pain	Swelling	Instability	Stiffness	Other
Flanigan [2]	135 1–2 years	NA	62 (46%)	73 (54%)	68%	47%	33%	26%	27%	22% weakness
Sandon [10]	205 3.2 years	STG or BPTB autograft	111 (54%)	94 (46%)	61%	61%	21%	39%	57%	19% locking
Lefevre [5]	497 primary 55 revision 1 year	Autografts	Primary 64% Revision 49%	Primary 36% Revision 51%	Primary 57% Revision 68%	NA	NA	NA	NA	NA
Lentz [6]	94 1 year	All types	52 (55%)	42 (45%)	40%	12%	7%	10%	NA	12% weakness
Kvist [3]	62 3–4 years	STG or BPTB autograft	33 (53%)	29 (47%)	35%	NA	NA	NA	NA	NA
Nwachukwu [8]	232 3.7 years	All types	156 (89%)	19 (11%)	33%	NA	NA	NA	NA	NA
McCullough [7]	94 2 years	NA	61 (65%)	33 (35%)	20% high school players 12% college players	NA	NA	NA	NA	NA
Lee [4]	45 5 years	STG autograft	28 (62%)	17 (38%)	18%	NA	NA	NA	NA	NA
Rodriguez-Roiz [9]	99 3 years	STG autograft	51 (52%)	48 (48%)	17%	17%	NA	6%	NA	NA
Smith [11]	77 3.6 years	Most BPTB autograft	32 (42%)	45 (58%)	13%	NA	NA	NA	NA	NA
Devgan [1]	48 5 years	STG or BPTB autograft	22 (46%)	26 (54%)	12.5%	NA	NA	NA	NA	NA

BPTB, bone-patellar tendon-bone, *NA* not assessed, *STG* semitendinosus-gracilis

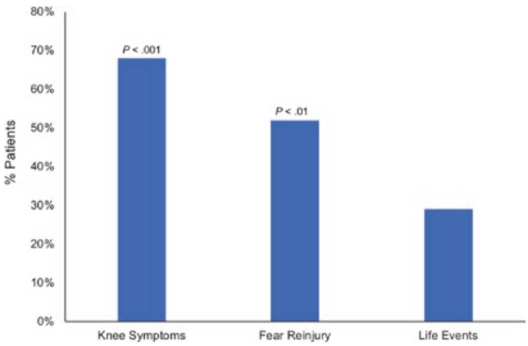


Fig. 2.1 A study of 73 patients surveyed 1–2 years postoperatively who did not return to their prior activity level found that residual knee symptoms were the most frequently cited reason, which was significantly greater than life events (such as job, family, childbirth, education, lack of time, lack of interest, or non-knee health reasons) [2]. Fear of reinjury was also cited significantly more frequently than life events

lowed for 3–4 years to determine RTS rates by Kvist et al. [3]. Problems with knee function was the primary reason 47% had not returned to preinjury levels. Other studies reported that knee symptoms prevented RTS in 12.3–33% of knees [1, 8, 9, 11].

In addition to understanding the impact residual knee symptoms have on preventing RTS, we believe it is also important to identify patients who participate in athletics but have frequent symptoms during or after competition [8, 12–14]. In 1983, one of us [14] described the *knee-abuser* and warned of the increased risk of the development of OA if pain, swelling, or instability was commonly experienced during or after sports activities. RTS is considered one of the most important outcome criteria after ACL reconstruc-

Fig. 2.2 The percent of men, women, and all patients combined reporting symptoms and problems that precluded the return to their preinjury activity level 1–2 years after ACL reconstruction [2]. A total of 68% of the 73 patients cited at least one persistent symptom as the reason they were unable to return

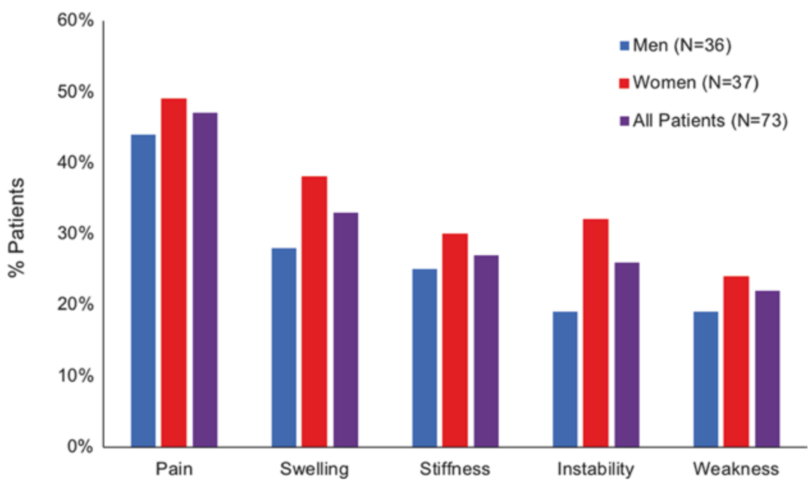
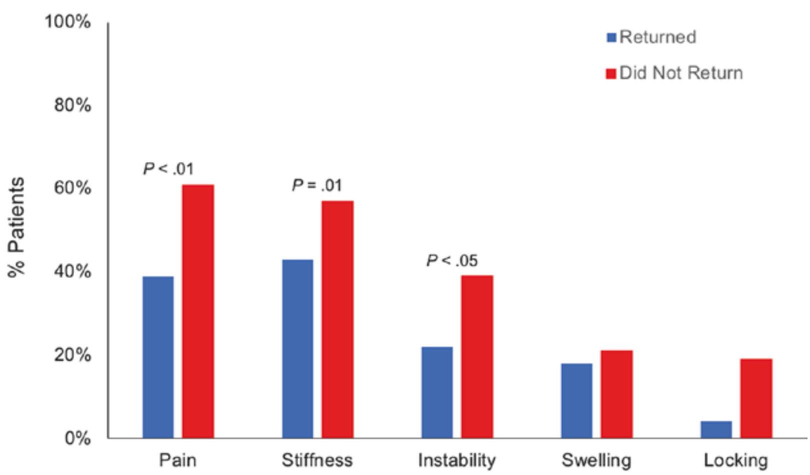


Fig. 2.3 Symptoms/problems during and/or after physical activity in 205 soccer players that underwent ACL autograft reconstruction surveyed a mean of 3.2 years postoperatively [10]



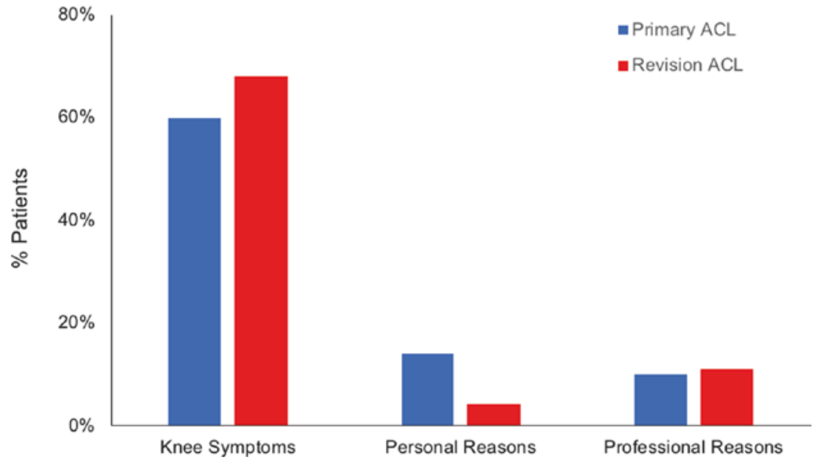


Fig. 2.4 Causes of decreasing activity levels or not resuming sports at 1 year postoperative in a group of 497 primary ACL reconstructions and 55 revision reconstructions [5]. There were no significant differences between the two groups in the percent with knee symptoms, personal reasons, or professional reasons

tion; however, we caution that including patients who are participating with pain, swelling, or giving-way in a *successful* category may be positively biasing a study's conclusions.

Unfortunately, few investigations have determined if patients who returned to sports did so without symptoms or whether they participated with problems. Nwachukwu et al. [8] followed 232 patients a mean of 3.7 years after ACL reconstruction. Although the authors reported a high percentage of patients who returned to preinjury activity levels (89%), 56% of these individuals reported problems of pain and/or limited performance. Smith et al. [11] reported on the outcome of 77 ACL-reconstructed patients. The overall incidence of patients competing in sports with major functional impairment was 21% at 12 months and 13% at final follow-up a mean of 3.6 years postoperatively.

We have reported in multiple studies results of ACL reconstruction by providing the number of patients who returned to either the same sports activity level, a higher level, or a lower level without problems; the number who participated (in any level) with symptoms; and the number who did not return to athletics either due to the knee condition or because of non-knee-related factors [15–18]. An example is shown in Table 2.2 in patients who underwent a primary ACL bone-patellar tendon-bone autograft reconstruction. Of 57 patients who had surgery for chronic ACL ruptures, 63% had returned to the same or a higher level of athletics without problems and 11% were playing with symptoms. Of 30 patients with acute ruptures, 53% had returned to the same or a higher level of athletics without problems and 11% were participating with problems. Patients who elect to participate even though they experience pain, swelling, or giving-way are counseled regarding the heightened potential for reinjuries and the development of early knee OA.

Table 2.2 Sports activity by subgroup using the Cincinnati Sports Activity Scale [17]

	Preoperatively (%)		Follow-up (%)	
	Chronic	Acute	Chronic	Acute
Type of sport				
Jumping, pivoting, cutting	9	76	16	50
Running, twisting, turning	21	10	23	17
Swimming, bicycling	21	14	47	17
Activities of daily living only	49	0	14	17
Change from preoperative levels				
Increased level, no symptoms			54	3
Same level, no symptoms			9	50
Decreased level, no symptoms			12	27
Playing with symptoms			11	3
No participation due to knee condition			12	0
No participation non-knee-related factors			2	17

2.2 Common Psychological and Psychosocial Barriers

2.2.1 Fear of Reinjury and Reinjury Anxiety

Research over the last two decades has demonstrated that psychological and psychosocial problems play an important role in the inability of athletes to return to preinjury activity levels after ACL reconstruction. A summary of basic terminology is shown in Table 2.3, and several review articles have described in detail the specific factors that may influence the postoperative recovery of an athlete [19–28]. Psychosocial factors involve both psychological and social aspects and are typically placed into four domains: affective, cognitive, behavioral, and social/cultural (Table 2.4). Many validated questionnaires have been used to determine the psychological status of athletes before and after ACL surgery (Table 2.5), the most frequent of which include the Anterior Cruciate Ligament-Return to Sport After Injury (ACL-RSI) and the Tampa Scale for Kinesiophobia (TSK). Chapter 23 discusses these questionnaires in further detail.

Fear of reinjury has been cited by many studies as a common barrier to RTS after ACL reconstruction (Table 2.6) [2, 3, 6, 7, 19, 21, 24, 29–37].

Table 2.3 Definitions of common psychological terms [22]

Term	Definition
Athletic identity	The degree to which one identifies with the athletic role
Catastrophizing	Assuming the worst-case scenario; interpreting any negative stimuli as disaster; dwell on inability to cope with pain
Kinesiophobia	An irrational and debilitating fear of physical movement; i.e., fear of reinjury
Locus of control	The manner in which an individual perceives his or her ability to control life events, belief in the relationship between action and outcome
Self-efficacy	Judgment of one's ability to organize and execute courses of action required to attain a desired goal
Reinjury anxiety	A negatively toned emotional response, with cognitive (negative thoughts and images) and somatic symptoms (feeling nauseous and tense) that arise due to the possibility of a reinjury occurring [46]

Table 2.4 Interrelated psychosocial domains of injured athletes [26, 27]

Domain	Attributes
Affective	Emotions, feelings, mood disturbances experienced after injury: loss, denial, anxiety, depression, fatigue, grief, confusion, frustration, burnout
Cognitive	Consciousness assessments (thoughts) made after injury: interpretations, appraisals, beliefs, self-efficacy, locus of control, coping strategies, self-perceptions of esteem and worth
Behavioral	Effort, actions, and activities regarding injury: influenced by cognitions and emotions. Coping skills such as goal setting, imagery, seeking out social support. Cyclical, may vary over days and weeks
Social/cultural	Perceptions of availability of emotional support and guidance from family, friends, coaches, medical personnel

Table 2.5 Validated psychological and psychosocial questionnaires

Questionnaire	Items assessed
Tampa Scale for Kinesiophobia (TSK) [3, 47]	Fear of movement/reinjury
Tampa Scale for Kinesiophobia Modified (TSK-11) [48]	Fear of movement/reinjury
ACL-Return to Sport After Injury (ACL-RSI) [49]	Emotions, confidence in performance, reinjury risk appraisal
Knee Self-Efficacy Scale (K-SES) [50]	Daily activities, sports and leisure activities, physical activities, knee function in the future
Injury-Psychological Readiness to Return to Sport Scale [51]	Confidence in ability to play, performance
Reinjury Anxiety Inventory [37]	Anxieties about rehabilitation and return to sport
Quick Inventory of Depressive Symptomatology [52]	Depression, sleep, appetite/weight
Multidimensional Health Locus of Control Scale (MHLC) [53]	Internal locus of control
State-Trait Anxiety Inventory [54]	State anxiety: how an athlete feels currently about various situations that may influence anxiety levels (i.e., not at all, very much so); temporary condition Trait anxiety: how an athlete feels in general toward various situations that may influence anxiety levels (i.e., almost never, almost always); long-standing condition

Table 2.6 Associations between failure to return to preinjury sport after ACL reconstruction and psychological barriers

Study	No. patients	Percent not returned preinjury sport (%)	Assessment methods for psychological factors	Significant associations with failure to return to preinjury sport level	
				Fear of reinjury	Other factors
Webster [38]	635	75	1 year postoperatively: ACL-RSI	Significant difference vs. returners ($P = 0.0001$)	NA
Ardern [19]	178	69	Preoperatively and 4 months postoperatively: ACL-RSI, SK, ERAIQ, SRLC; non-validated ISP; patients followed 1 year postoperatively	4 months p.o. OR 1.17 ($P = 0$ 0.01)	Psychological readiness: preop OR 1.03 ($P < 0.01$); 4 months p.o. OR 1.10 ($P < 0.001$) Locus of control 4 months p.o.: OR 0.95 ($P = 0.05$)
Faltstrom [30]	182	48	1.5 years postoperatively: ACL-RSI, Swedish Scales of Personality, Sport Multidimensional Perfectionism Scale, non-validated questionnaire	Present in 25% on non-returners	Low motivation ($P < 0.001$), psychological readiness ($P < 0.001$)
Flanigan [2]	135	54	1–2 years postoperatively: non-validated telephone survey	Present in 52% of non-returners	NA
McCullough [7]	94	35	2 years postoperatively: non-validated questionnaire	Present in 53% of high school and 50% collegiate non-returners	NA
Muller [34]	40	20	6 months postoperatively: TSK	Present in 100% of non-returners; significant difference vs. returners ($P = 0.01$)	NA
Kvist [3]	62	69	3–4 years postoperatively: TSK	Present in 24% of non-returners; significant difference vs. returners ($P = 0.01$)	NA
Langford [32]	87	49	1 year postoperatively: ACL-RSI, ERAIQ	Significant difference returners vs. non-returners ($P = 0.001$)	NA
Tripp [36]	49	NA	1 year postoperatively: TSK, S-POMS, PCS, Sport Self-Confidence Inventory	Only predictor of return to preinjury sport level ($P = 0.01$)	Negative mood associated with lack of confidence in ability to engage in sports ($P < 0.01$)
Lentz [6]	94	45	1 year postoperatively: TSK	Present in 45% of non-returners; significant difference vs. returners ($P < 0.001$)	NA

ACL-RSI Anterior Cruciate Ligament-Return to Sport After Injury, *ERAIQ* Emotional Responses of Athletes to Injury Questionnaire, *K-SES* Knee Self-Efficacy Scale, *ISP* Incredibly Short Profile of Mood States, *NA* not assessed, *OR* odds ratio, *PCS* Pain Catastrophizing Scale, *S-POMS* Shortened Profile of Mood States, *SRLC* Sport Rehabilitation Locus of Control, *TSK* Tampa Scale for Kinesiophobia (see also Table 2.5)

Table 2.7 Association of patient rating of overall knee function on postoperative activity level and psychological factors 3 years after ACL reconstruction [42]

Variable	Patient rating overall knee function			*P* value
	Satisfied (*n* = 74)	Mostly satisfied (*n* = 49)	Dissatisfied (*n* = 47)	
Returned to preinjury activity level				
Yes (%)	61[a]	29	22	NA
No (%)	39[a]	71	78	NA
Psychological factors, mean points (95% CI)				
K-SES (range, 0–10)	8.3 (7.9–8.7)[a]	6.9 (6.4–7.4)[c]	4.8 (4.3–5.2)	<0.001
TSK (range, 17–68)	31.1 (29.4–32.8)[a]	35.2 (33.2–37.2)[c]	41.7 (39.7–43.7)	<0.001
ACL-RSI (range, 1–10)	6.2 (5.8–6.7)[a]	4.7 (4.1–5.2)[c]	3.3 (2.8–3.9)	<0.001
MHLC (range, 6–36)	27.5 (26.1–28.9)[b]	25.7 (24.0–27.4)	23.2 (21.5–24.9)	0.001

ACL-RSI Anterior Cruciate Ligament-Return to Sport After Injury, *CI* confidence interval, *K-SES* Knee Self-Efficacy Scale, *MHLC* Multidimensional Health Locus of Control scale, *TSK* Tampa Scale for Kinesiophobia

[a]Significant difference between satisfied and mostly satisfied/dissatisfied groups

[b]Significant difference between satisfied and dissatisfied groups

[c]Significant difference between mostly satisfied and dissatisfied groups

Fear has been measured using the ACL-RSI and the TSK or determined through patient interviews. For instance, Flanigan et al. [2] contacted 135 patients (67 men, 68 women) to determine common factors for failure to RTS 1–2 years after ACL reconstruction. Fear of reinjury, documented in 52% of the patients that did not return to preinjury activity levels, was one of the most common reasons and was not associated with gender. McCullough et al. [7] surveyed 68 high school and 26 collegiate American football players 2 years post-ACL reconstruction of whom 37% and 31%, respectively, failed to return to their preinjury activity level. Fear of reinjury was the second most common reason these athletes did not return to football.

Webster et al. [38] examined factors associated with psychological readiness to RTS in a cohort of 635 patients followed a mean of 12 ± 1 months after ACL reconstruction. Only 25% of the patients had returned to competitive sport, with significant differences noted between those who returned and those who had not in ACL-RSI scores (79 ± 17 and 60 ± 23 points, respectively, $P = 0.0001$). Statistically significant differences were also found between RTS groups in International Knee Documentation Committee (IKDC) subjective form scores, single-hop limb symmetry index, age, and gender. Only 17% of female patients RTS compared with 30% of male patients.

Lentz et al. [6] followed 94 patients a year after ACL reconstruction and found that 45% had not returned to preinjury activity levels. Of these, 45% reported fear of reinjury/lack of confidence in the knee as the primary reason for not returning. Patients that did not return had a significantly lower TSK score compared with those that did return to sports (15.3 ± 4.1 and 19.6 ± 4.7 points, respectively, $P < 0.001$). Other studies have also reported statistically significant differences in TSK scores between patients that returned and did not return to preinjury activity levels [3, 34]. Tripp et al. reported that fear of reinjury assessed with TSK scores was predictive of RTS ($P < 0.01$). The authors noted this was an interesting finding because their cohort of 49 patients reported very little or no pain 1 year postoperatively, scoring a mean of 0.5 ± 1.2 on a visual analogue scale that ranged from 0 to 10.

Langford et al. [32] reported significant differences in ACL-RSI mean scores between 44 patients who RTS and 43 who had not returned 1 year post ACL reconstruction (72.05 ± 16.25 and 58.61 ± 18.34 points, respectively, $P = 0.001$). Lower scores on this scale represent increased fear of reinjury, decreased confidence, and emotional difficulties. Rosso et al. [35] reported that ACL-RSI scores were predictive of RTS in both univariate and multiple logistic regression models in a cohort of 161 ACL-reconstructed patients ($P < 0.001$ and $P = 0.0001$, respectively), as a lower ACL-RSI score was associated with a lower RTP rate.

A specific questionnaire was designed for reinjury anxiety, which Walker et al. [37] specified was different from fear of reinjury. While fear contains a certainty of sources of danger, anxiety is ambiguous and is connected to anticipation and imagination of what might happen. Each individual athlete has their own perceived injury risk, which may be flexible and may change for different situations. To date, this questionnaire has not been used in ACL-reconstructed cohorts. Other studies used a single question [39] or the validated State-Trait Anxiety Inventory [40] to assess the effects of rehabilitation interventions (relaxation, imagery, and modeling) on anxiety after ACL reconstruction. For instance, Cupal and Brewer [41] studied the effect of 10 relaxation and guided imagery sessions spaced 2 weeks apart over a 6-month period after ACL reconstruction. Compared with placebo and control groups, patients in the treatment group had significantly reduced injury anxiety scores 24 weeks postoperatively ($P < 0.05$).

2.2.2 Self-Efficacy

In contrast to fear or anxiety of reinjury, high scores of perceived self-efficacy (on the Knee Self-Efficacy scale [K-SES]) measured preoperatively were found in one study to be predictive of physical activity 1 year postoperatively [41]. Ardern et al. [42] used the K-SES, TSK, and ACL-RSI questionnaires in 177 patients a mean of 3 years after ACL reconstruction and reported that the odds of being satisfied with the outcome increased by a factor of 3 with higher self-efficacy, greater knee-related quality of life, and returning to preinjury activity. In this study, 74 patients rated their overall outcome as satisfied, 49 as mostly satisfied, and 47 as dissatisfied (Table 2.6). A significantly greater percentage of patients RTS in the satisfied group compared with the mostly satisfied and dissatisfied groups (61% versus 29% and 22%, respectively, $P = 0.001$).

Self-efficacy was found by Thomee et al. [43] to be significantly higher before ACL reconstruction in patients with higher baseline activity levels (Tegner levels 7–10) compared with patients with lower activity levels (Tegner level 3–6; $P = 0.005$). One year after surgery, scores on the K-SES correlated with KOOS subscales ($R = 0.41–0.72$). Self-efficacy improved throughout the first postoperative year, but the improvement was only partly due to a decrease in symptoms. The authors noted that the increase in perceived self-efficacy may be explained by other factors that were not measured, such as coping strategies, health locus of control, or quality of life. In another study, Thomee et al. [41] reported that preoperative K-SES scores in 38 patients were predictive of return to previous sports activity levels 1 year after ACL reconstruction (odds ratio 2.1, $P < 0.05$) and correlated with KOOS quality of life scores (odds ratio 1.4, $P < 0.05$).

Gobbi et al. [44] developed a psychovitality questionnaire that was administered before ACL reconstruction in 100 patients. Patient expectations regarding treatment outcome and motivation to resume preinjury activity levels were analyzed, with scores ranging from 3 to 18 points. Two years postoperatively, a significant difference was found in scores between patients who RTS and those who did not; a score ≥15 points was found in 67% of those who returned compared with just 29% of those who failed to return ($P < 0.001$).

2.2.3 Locus of Control

Health locus of control refers to the manner in which an individual perceives his or her ability to control life events. A high internal locus of control score indicates a strong perception of life events as being a consequence of one's behavior, whereas a low internal score indicates a strong perception of life events being more determined by fate, chance, or factors beyond a person's control. Nyland et al. [45] determined relationships between scores from the Multidimensional Health Locus of Control (MHLC) scale and the Knee Outcome Survey (KOS) and the IKDC Subjective rating scale in 198 patients a mean of 5.1 ± 2.9 years after ACL reconstruction. Patients with high internal locus of control scores (≥ 25 points) had significantly greater scores compared to patients with low internal locus of control scores for KOS-sports activity level scores

(85.2 ± 18 and 70 ± 29, respectively, $P < 0.0001$) and IKDC scores (80.9 ± 17.7 and 68.3 ± 25.2, respectively, $P < 0.0001$).

Ardern et al. [19] used the Sport Rehabilitation Locus of Control (SRLC) scale in 178 ACL-reconstructed patients to determine if correlations existed between scale scores and return to preinjury sports activity levels. SRLC scores collected 4 months postoperatively were predictive of RTS (odds ratio 0.96, $P < 0.05$). Other predictive factors in this study of RTS included higher ACL-RSI scores (OR, 1.10) and TSK scores (OR 1.21). Thus, it appears that high internal locus of control and self-efficacy scores are predictive of achieving preinjury sports activity levels after ACL reconstruction. te Wierike et al. [27] remarked that these qualities represent overall confidence which in turn influences motivation for rehabilitation.

2.3 Conclusions

Some of the most common physical obstacles to RTS after ACL reconstruction are residual knee symptoms of pain, swelling, and/or instability. Recent research has demonstrated that psychological and psychosocial problems also play an important role in the inability of athletes to return to preinjury activity levels. Fear of reinjury or reinjury anxiety, poor perceived self-efficacy, low levels of internal locus of control, poor motivation, and emotional disturbances have all correlated with failure to RTS. Knowledge of these factors is crucial for those involved with the medical management of athletes in order to screen, detect, and initiate treatment and counseling.

References

1. Devgan A, Magu NK, Siwach RC, Rohilla RK, Sangwan SS. Functional outcome in athletes at five years of arthroscopic anterior cruciate ligament reconstruction. ISRN Orthop. 2011;2011:1–6.
2. Flanigan DC, Everhart JS, Pedroza A, Smith T, Kaeding CC. Fear of reinjury (kinesiophobia) and persistent knee symptoms are common factors for lack of return to sport after anterior cruciate ligament reconstruction. Arthroscopy. 2013;29(8):1322–9. https://doi.org/10.1016/j.arthro.2013.05.015.
3. Kvist J, Ek A, Sporrstedt K, Good L. Fear of re-injury: a hindrance for returning to sports after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2005;13(5):393–7. https://doi.org/10.1007/s00167-004-0591-8.
4. Lee DY, Karim SA, Chang HC. Return to sports after anterior cruciate ligament reconstruction – a review of patients with minimum 5-year follow-up. Ann Acad Med Singap. 2008;37(4):273–8.
5. Lefevre N, Klouche S, Mirouse G, Herman S, Gerometta A, Bohu Y. Return to sport after primary and revision anterior cruciate ligament reconstruction: a prospective comparative study of 552 patients from the FAST cohort. Am J Sports Med. 2017;45(1):34–41. https://doi.org/10.1177/0363546516660075.
6. Lentz TA, Zeppieri G Jr, Tillman SM, Indelicato PA, Moser MW, George SZ, Chmielewski TL. Return to preinjury sports participation following anterior cruciate ligament reconstruction: contributions of demographic, knee impairment, and self-report measures. J Orthop Sports Phys Ther. 2012;42(11):893–901. https://doi.org/10.2519/jospt.2012.4077.
7. McCullough KA, Phelps KD, Spindler KP, Matava MJ, Dunn WR, Parker RD, Group M, Reinke EK. Return to high school- and college-level football after anterior cruciate ligament reconstruction: a Multicenter Orthopaedic Outcomes Network (MOON) cohort study. Am J Sports Med. 2012;40(11):2523–9. https://doi.org/10.1177/0363546512456836.
8. Nwachukwu BU, Voleti PB, Berkanish P, Chang B, Cohn MR, Williams RJ 3rd, Allen AA. Return to play and patient satisfaction after ACL reconstruction: study with minimum 2-year follow-up. J Bone Joint Surg Am. 2017;99(9):720–5. https://doi.org/10.2106/JBJS.16.00958.
9. Rodriguez-Roiz JM, Caballero M, Ares O, Sastre S, Lozano L, Popescu D. Return to recreational sports activity after anterior cruciate ligament reconstruction: a one- to six-year follow-up study. Arch Orthop Trauma Surg. 2015;135(8):1117–22. https://doi.org/10.1007/s00402-015-2240-8.
10. Sandon A, Werner S, Forssblad M. Factors associated with returning to football after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2015;23(9):2514–21. https://doi.org/10.1007/s00167-014-3023-4.
11. Smith FW, Rosenlund EA, Aune AK, MacLean JA, Hillis SW. Subjective functional assessments and the return to competitive sport after anterior cruciate ligament reconstruction. Br J Sports Med. 2004;38(3):279–84.
12. Ardern CL, Taylor NF, Feller JA, Webster KE. Return-to-sport outcomes at 2 to 7 years after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2012;40(1):41–8. https://doi.org/10.1177/0363546511422999.
13. Kocher MS, Steadman JR, Briggs K, Zurakowski D, Sterett WI, Hawkins RJ. Determinants of patient

satisfaction with outcome after anterior cruciate ligament reconstruction. J Bone Joint Surg Am. 2002;84-A(9):1560–72.
14. Noyes FR, Mooar PA, Matthews DS, Butler DL. The symptomatic anterior cruciate-deficient knee. Part I: the long-term functional disability in athletically active individuals. J Bone Joint Surg Am. 1983;65(2):154–62.
15. Noyes FR, Barber-Westin SD. Reconstruction of the anterior cruciate ligament with human allograft. Comparison of early and later results. J Bone Joint Surg Am. 1996;78(4):524–37.
16. Noyes FR, Barber-Westin SD. Anterior cruciate ligament reconstruction with autogenous patellar tendon graft in patients with articular cartilage damage. Am J Sports Med. 1997;25(5):626–34.
17. Noyes FR, Barber-Westin SD. A comparison of results in acute and chronic anterior cruciate ligament ruptures of arthroscopically assisted autogenous patellar tendon reconstruction. Am J Sports Med. 1997;25(4):460–71.
18. Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: results using a quadriceps tendon-patellar bone autograft. Am J Sports Med. 2006;34(4):553–64. https://doi.org/10.1177/0363546505281812.
19. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2013;41(7):1549–58. https://doi.org/10.1177/0363546513489284.
20. Ardern CL, Taylor NF, Feller JA, Webster KE. A systematic review of the psychological factors associated with returning to sport following injury. Br J Sports Med. 2013;47(17):1120–6. https://doi.org/10.1136/bjsports-2012-091203.
21. Ardern CL. Anterior cruciate ligament reconstruction-not exactly a one-way ticket Back to the Preinjury level: a review of contextual factors affecting return to sport after surgery. Sports Health. 2015;7(3):224–30. https://doi.org/10.1177/1941738115578131.
22. Christino MA, Fantry AJ, Vopat BG. Psychological aspects of recovery following anterior cruciate ligament reconstruction. J Am Acad Orthop Surg. 2015;23(8):501–9. https://doi.org/10.5435/JAAOS-D-14-00173.
23. Cozzi AL, Dunn KL, Harding JL, Valovich McLeod TC, Welch Bacon CE. Kinesiophobia after anterior cruciate ligament reconstruction in physically active individuals. J Sport Rehabil. 2015;24(4):434–9. https://doi.org/10.1123/jsr.2014-0196.
24. Czuppon S, Racette BA, Klein SE, Harris-Hayes M. Variables associated with return to sport following anterior cruciate ligament reconstruction: a systematic review. Br J Sports Med. 2014;48(5):356–64. https://doi.org/10.1136/bjsports-2012-091786.
25. Everhart JS, Best TM, Flanigan DC. Psychological predictors of anterior cruciate ligament reconstruction outcomes: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2015;23(3):752–62. https://doi.org/10.1007/s00167-013-2699-1.
26. Podlog L, Heil J, Schulte S. Psychosocial factors in sports injury rehabilitation and return to play. Phys Med Rehabil Clin N Am. 2014;25(4):915–30. https://doi.org/10.1016/j.pmr.2014.06.011.
27. te Wierike SC, van der Sluis A, van den Akker-Scheek I, Elferink-Gemser MT, Visscher C. Psychosocial factors influencing the recovery of athletes with anterior cruciate ligament injury: a systematic review. Scand J Med Sci Sports. 2013;23(5):527–40. https://doi.org/10.1111/sms.12010.
28. Wiese-Bjornstal DM. Psychology and socioculture affect injury risk, response, and recovery in high-intensity athletes: a consensus statement. Scand J Med Sci Sports. 2010;20(Suppl 2):103–11. https://doi.org/10.1111/j.1600-0838.2010.01195.x.
29. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med. 2014;48(21):1543–52. https://doi.org/10.1136/bjsports-2013-093398.
30. Faltstrom A, Hagglund M, Kvist J. Factors associated with playing football after anterior cruciate ligament reconstruction in female football players. Scand J Med Sci Sports. 2016;26(11):1343–52. https://doi.org/10.1111/sms.12588.
31. Hsu CJ, Meierbachtol A, George SZ, Chmielewski TL. Fear of Reinjury in athletes. Sports Health. 2017;9(2):162–7. https://doi.org/10.1177/1941738116666813.
32. Langford JL, Webster KE, Feller JA. A prospective longitudinal study to assess psychological changes following anterior cruciate ligament reconstruction surgery. Br J Sports Med. 2009;43(5):377–8.
33. Lentz TA, Zeppieri G Jr, George SZ, Tillman SM, Moser MW, Farmer KW, Chmielewski TL. Comparison of physical impairment, functional, and psychosocial measures based on fear of reinjury/lack of confidence and return-to-sport status after ACL reconstruction. Am J Sports Med. 2015;43(2):345–53. https://doi.org/10.1177/0363546514559707.
34. Muller U, Kruger-Franke M, Schmidt M, Rosemeyer B. Predictive parameters for return to pre-injury level of sport 6 months following anterior cruciate ligament reconstruction surgery. Knee Surg Sports Traumatol Arthrosc. 2015;23(12):3623–31. https://doi.org/10.1007/s00167-014-3261-5.
35. Rosso F, Bonasia DE, Cottino U, Cambursano S, Dettoni F, Rossi R. Factors affecting subjective and objective outcomes and return to play in anterior cruciate ligament reconstruction: a retrospective cohort study. Joints. 2018;6(1):23–32. https://doi.org/10.1055/s-0038-1636931.
36. Tripp DA, Stanish WD, Ebel-Lam A, Brewer BW, Birchard J. Fear of reinjury, negative affect, and catastrophizing predicting return to sport in recreational athletes with anterior cruciate ligament injuries at

1 year postsurgery. Sport Exerc Perform Psychol. 2011;1(S):38–48.
37. Walker N, Thatcher J, Lavallee D. A preliminary development of the re-injury anxiety inventory (RIAI). Phys Ther Sport. 2010;11(1):23–9. https://doi.org/10.1016/j.ptsp.2009.09.003.
38. Webster KE, Nagelli CV, Hewett TE, Feller JA. Factors associated with psychological readiness to return to sport after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2018;46(7):1545–50. https://doi.org/10.1177/0363546518773757.
39. Cupal DD, Brewer BW. Effects of relaxation and guided imagery on knee strength, reinjury, anxiety, and pain following anterior cruciate ligament reconstruction. Rehabil Psychol. 2001;46(1):28–43.
40. Maddison R, Prapavessis H, Clatworthy M. Modeling and rehabilitation following anterior cruciate ligament reconstruction. Ann Behav Med. 2006;31(1):89–98. https://doi.org/10.1207/s15324796abm3101_13.
41. Thomee P, Wahrborg P, Borjesson M, Thomee R, Eriksson BI, Karlsson J. Self-efficacy of knee function as a pre-operative predictor of outcome 1 year after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2008;16(2):118–27. https://doi.org/10.1007/s00167-007-0433-6.
42. Ardern CL, Osterberg A, Sonesson S, Gauffin H, Webster KE, Kvist J. Satisfaction with knee function after primary anterior cruciate ligament reconstruction is associated with self-efficacy, quality of life, and returning to the Preinjury physical activity. Arthroscopy. 2016;32(8):1631–1638 e1633. https://doi.org/10.1016/j.arthro.2016.01.035.
43. Thomee P, Wahrborg P, Borjesson M, Thomee R, Eriksson BI, Karlsson J. Self-efficacy, symptoms and physical activity in patients with an anterior cruciate ligament injury: a prospective study. Scand J Med Sci Sports. 2007;17(3):238–45. https://doi.org/10.1111/j.1600-0838.2006.00557.x.
44. Gobbi A, Francisco R. Factors affecting return to sports after anterior cruciate ligament reconstruction with patellar tendon and hamstring graft: a prospective clinical investigation. Knee Surg Sports Traumatol Arthrosc. 2006;14(10):1021–8. https://doi.org/10.1007/s00167-006-0050-9.
45. Nyland J, Cottrell B, Harreld K, Caborn DN. Self-reported outcomes after anterior cruciate ligament reconstruction: an internal health locus of control score comparison. Arthroscopy. 2006;22(11):1225–32.
46. Wadey R, Podlog L, Hall M, Hamson-Utley J, Hicks-Little C, Hammer C. Reinjury anxiety, coping, and return-to-sport outcomes: a multiple mediation analysis. Rehabil Psychol. 2014;59(3):256–66. https://doi.org/10.1037/a0037032.
47. Vlaeyen JW, Kole-Snijders AM, Boeren RG, van Eek H. Fear of movement/(re)injury in chronic low back pain and its relation to behavioral performance. Pain. 1995;62(3):363–72.
48. Woby SR, Roach NK, Urmston M, Watson PJ. Psychometric properties of the TSK-11: a shortened version of the Tampa scale for Kinesiophobia. Pain. 2005;117(1–2):137–44. https://doi.org/10.1016/j.pain.2005.05.029.
49. Webster KE, Feller JA, Lambros C. Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. Phys Ther Sport. 2008;9(1):9–15. https://doi.org/10.1016/j.ptsp.2007.09.003.
50. Thomee P, Wahrborg P, Borjesson M, Thomee R, Eriksson BI, Karlsson J. A new instrument for measuring self-efficacy in patients with an anterior cruciate ligament injury. Scand J Med Sci Sports. 2006;16(3):181–7.
51. Glazer DD. Development and preliminary validation of the injury-psychological readiness to return to sport (I-PRRS) scale. J Athl Train. 2009;44(2):185–9. https://doi.org/10.4085/1062-6050-44.2.185.
52. Trivedi MH, Rush AJ, Ibrahim HM, Carmody TJ, Biggs MM, Suppes T, Crismon ML, Shores-Wilson K, Toprac MG, Dennehy EB, Witte B, Kashner TM. The Inventory of Depressive Symptomatology, Clinician Rating (IDS-C) and Self-Report (IDS-SR), and the Quick Inventory of Depressive Symptomatology, Clinician Rating (QIDS-C) and Self-Report (QIDS-SR) in public sector patients with mood disorders: a psychometric evaluation. Psychol Med. 2004;34(1):73–82.
53. Wallston KA, Stein MJ, Smith CA. Form C of the MHLC scales: a condition-specific measure of locus of control. J Pers Assess. 1994;63(3):534–53. https://doi.org/10.1207/s15327752jpa6303_10.
54. Spielberger C, Gorsuch R, Lushene R, Vagg P, Jacobs G. Manual for the state-trait anxiety inventory. Palo Alto, CA: Consulting Psychologists Press; 1983.

3 The Arthritis Barrier: Long-Term Effects of ACL Trauma on Knee Joint Health

Emily Eichner and Bruce Beynnon

3.1 Epidemiology of Post-Traumatic Osteoarthritis Following ACL Trauma

The knee joint is a common location of osteoarthritis (OA). As Lohmander et al. explain, "Osteoarthritis describes a common, age-related, heterogeneous group of disorders characterized by focal areas of loss of articular cartilage in synovial joints associated with varying degrees of osteophyte formation, subchondral bone change, and synovitis" [1]. In OA, cartilage undergoes gradual proteolytic degradation of matrix, with increased synthesis of matrix components by chondrocytes. Early in the disease process, cartilage swelling, surface fibrillation, and cleft formation occur, and in later stages, cartilage volume loss appears [1]. In advanced stages, plain radiographs can detect structural changes such as joint space loss, osteophytes, subchondral sclerosis, and bone cysts [1]. Since OA is an insidious disease, early radiographic-based structural changes are often evident long before any clinical symptoms are present and are not necessarily associated with symptoms or functional abilities [1, 2]. Recent advancements in magnetic resonance imaging (MRI) technologies have enabled the assessment of cartilage, meniscus, synovium, and bone in detail and feature earlier detection of the disease process than the use of radiographs alone. For example, MRI can be used to measure the change in articular cartilage thickness, progression of bone marrow lesions, synovial changes, capsule thickening, meniscus maceration, and extrusion [1]. MRI-based T1ρ and T2 relaxation times can be applied to study early cartilage degeneration in advance of radiographic changes [3]. T1ρ relaxation time correlates with the articular cartilage proteoglycan content and T2 relaxation time correlates with the collagen structure and water content such that higher relaxation times indicate worse cartilage matrix health [4–6]. Delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) is another MRI-based measurement technique that detects cartilage degeneration by estimating the glycosaminoglycans (GAGs) content, which are negatively charged molecules that attach to the matrix protein aggrecan and regulate the Donian osmotic gradient that attracts water into the articular cartilage, the primary cartilage matrix component that provides efficient transmission of contact stress across the knee joint [6, 7]. Shorter T1Gd correlates with lower cartilage GAG content, indicating decreased cartilage health [7]. Of note, radiographic measurement of tibiofemoral joint space loss and MRI-based measurement of tibiofemoral cartilage thickness are not correlated,

E. Eichner · B. Beynnon (✉)
Department of Orthopaedics and Rehabilitation, Robert Larner College of Medicine, University of Vermont, Burlington, VT, USA
e-mail: emily.eichner@med.uvm.edu; bruce.beynnon@uvm.edu

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_3

and these two methods of examining changes associated with the onset and early progression of OA should not be used interchangeably [8].

Symptomatic post-traumatic osteoarthritis (PTOA) represents a subset of OA and is a substantial burden to society, as it is estimated that PTOA accounts for 12% of OA cases (12.7 million people), costing the healthcare system an estimated 3 billion dollars annually [9]. Trauma to the anterior cruciate ligament (ACL), menisci, or dislocation of the patella are the most common injuries that place individuals at increased risk of developing PTOA about the knee. The reported prevalence of knee PTOA following ACL trauma varies widely between studies due to many significant variables affecting its development, including the time from injury to follow-up, concomitant injuries, the delay between injury and treatment, the type of treatment, activity level at the time of return to sport (RTS) and preinjury activities, and heterogeneous diagnostic criteria used to characterize the disease. For example, Lohmander et al. reported that 10–90% of ACL-injured subjects have evidence of PTOA at follow-up intervals that ranged between 10 and 20 years after the index injury [1]. A meta-analysis by Ajuied et al. reported ACL injury to be associated with a 3.89 relative risk (RR) of developing any PTOA and a 3.64 RR of developing moderate or severe PTOA (assessed using Kellgren and Lawrence classification or radiographs) at a mean follow-up interval of 10 years [10]. The factors associated with the increased risk of developing PTOA after ACL injury include increased body mass index (BMI) [11–14], female sex [12, 15], increased age [15], smoking [12, 13], and lower education level [12]. Another potential risk factor may be genetic predisposition to the early onset of PTOA. For example, two studies have linked hand OA with increased frequency and severity of knee OA after meniscectomy [16, 17] suggesting that there may be genetic factors involved with the onset and progression of disease following meniscus surgery. In contrast, a more recent study that focused on ACL-injured patients did not find a relationship between the hand OA and knee OA rates [18]. At the current point in time, it is unclear if and how genetics are involved with the development of PTOA following ACL injury.

3.2 Effect of Sport on PTOA Following ACL Trauma

Because the knees of athletes that compete at high levels are exposed to elevated contact stress levels in comparison to the general population's, many studies have attempted to understand the PTOA rates in an athlete or sport-specific manner. One systematic review revealed OA rates, irrespective of the cause, to be 30% of former athletes [19]. Another systematic review by Driban et al. reported between three and seven times higher prevalence of OA in athletes that participate in soccer, elite long-distance running, weightlifting, and wrestling (prevalence ranging 4.2–8.5%) compared with nonsports participants (prevalence ranging 1.3–2.3%). Elite-level basketball, boxing, shooting, and track and field did not have a higher prevalence of OA compared with nonsports participants; however, these findings do not consider joint injury history [20]. Driban et al.'s review also found that joint injury may be the main cause of the high rates of OA in athletes that take part in soccer and ice hockey [20]. A study of elite football athletes participating in the National Football League (NFL) Combine (age range, 20–26 years) reported a 15% prevalence of OA based on MRI or radiographic imaging, and this correlated with prior ACL injury, knee surgery, and increased BMI [21]. The high ACL injury rates in these sports, along with the high stress demands placed on the knee could combine to increase the risk of OA in athletes. Two landmark studies demonstrated 51% of female soccer players (mean age, 31 years) and 41% of male soccer players (mean age, 38 years) had radiographic PTOA 12–14 years after ACL injury, with 80% showing radiographic features of OA in both groups [22, 23]. Simon et al. revealed PTOA rates to be 76.7% in former Division I collegiate athletes (age range, 40–65 years) who had a knee injury requiring surgery during their collegiate career

[24]. In comparison, Losina et al. reported the overall prevalence of symptomatic OA in the general population aged 45–54 years old to be 3.61% for nonobese men and 4.26% for non-obese women [25]. In addition to increased joint stresses and injuries that athletes experience, there are other risk factors that may be linked to high OA rates. For example, Madaleno et al. suggest that the high prevalence of former athletes becoming overweight after retiring could raise OA risk because increased BMI is the risk factor for PTOA [19]. The increased prevalence of OA in the athlete population, especially PTOA, is significant as the studies discussed show that these athletes with OA are often young. The estimated mean age at diagnosis of OA for the general population is 53.5 years [25]. Since athletes may be at risk of experiencing OA at younger ages than the general population, this may have important economic, medical, and quality-of-life implications to consider.

3.3 Effect of ACL Injury and Concomitant Articular Cartilage Injury on PTOA

It is relatively rare that ACL trauma occurs in isolation as it is often accompanied by injury to other structures about the knee such as articular cartilage lesions (46% prevalence), traumatic bone marrow lesions (80% prevalence), meniscus tears (60–75% prevalence), and other ligament tears (5–24% prevalence) [26–33]. This creates a considerable clinical concern because ACL injury combined with trauma to the other structures about the knee significantly increases the risk of developing PTOA in comparison to ACL injury in isolation [1, 34]. Indeed, Risberg et al. revealed that subjects who have suffered ACL injury and undergone reconstruction should not be considered as a homogeneous group because those suffering ACL trauma in combination with injury to other articular and meniscal cartilage structures undergo progression to radiographic and symptomatic PTOA at a much faster rate than those without concomitant injury [34]. This is an important concern because at the time of ACL reconstruction, the patient age, surgical delay, and sex are independently associated with the frequency and location of articular cartilage injury, an early harbinger of PTOA [34, 35]. For example, Keays et al. reported that chondral damage is a strong predictor of future development of tibiofemoral PTOA following ACL reconstruction [36], and articular cartilage abnormalities at the time of ACL injury are associated with worse results and patient-reported outcomes at 2- and 6-year follow-up intervals [12, 13]. Slauterbeck et al. reported patients that are ≥25 years of age at the time of ACL reconstructions are more likely to have multiple articular cartilage lesions throughout the knee (7.7% compared with 1.3% for those <25 years of age) and present with more isolated medial femoral condyle lesions (24.2% compared with 13.3%) [35]. Further, at the time of ACL reconstruction, female patients have a greater proportion of grade 1 articular cartilage lesions of the medial femoral condyle (29% compared with 16% for the males), while male patients have a greater proportion of grade 3 and 4 cartilage lesions of the medial femoral condyle (49% compared with 35% for the females) [35]. Patients that are ≥35 years of age at the time of ACL reconstruction have femoral articular cartilage lesions located more frequently on the medial side in comparison to those <35 years of age [35].

It is important to appreciate that ACL trauma not only has an immediate effect on the knee regarding PTBMLs, but it also affects articular cartilage structure in terms of thickening and thinning of the articular cartilage [37]. Argentieri et al. reported that ACL-injured females had significant changes in articular cartilage thickness in the injured knee compared to the uninjured knee at a median of 15 days post injury, with an increased thickness in the central region of the medial tibial cartilage and thinning of the medial posterior cartilage region (Fig. 3.1) [37]. The medial central areas of increased thickness may indicate acute loss of proteoglycans from the cartilage caused by blunt impact forces, resulting in a shift in water content [37]. The medial posterior areas of cartilage thinning may be the result of injury causing increased contact stress

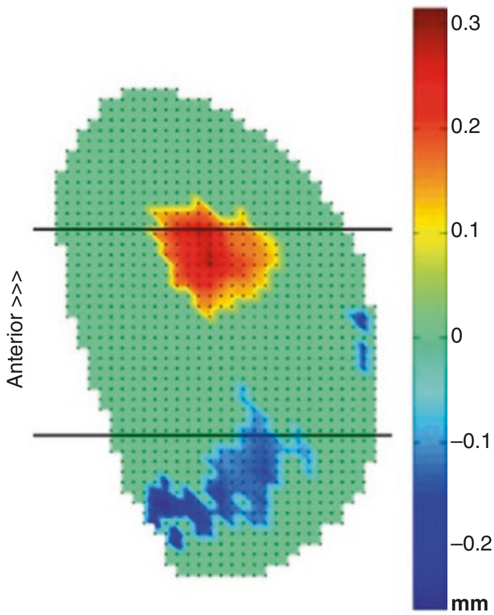


Fig. 3.1 Significant injured-to-uninjured side differences in articular cartilage thickness found in the medial compartment within ACL-injured females. Articular cartilage was thicker in the central region and thinner in the posterior region of ACL-injured knees (From Argentieri et al. [37])

in this region that does not have the material and structural properties of the cartilage normally suited to support such contact stress [37].

3.4 Effect of ACL Injury and Post-Traumatic Bone Marrow Lesions on PTOA

Another common concomitant injury seen with ACL disruption is post-traumatic bone marrow lesions (PTBMLs). These occur at the locations of high-impact forces between the tibial and femoral articular surfaces at the time of an ACL tear [38] and are thought to be associated with edema, hemorrhage, and trabecular microfractures [39–41]. Sievanen et al. used dual-energy X-ray absorptiometry to study the change in periarticular bone about the knee and revealed rapid decreases of bone mineral density soon after an ACL disruption, followed by a phase of partial recovery [42]. Although the independent effects of ACL disruption and ACL reconstruction on bone mineral density and mass are not well understood, reduced bone mass in the injured knee following ACL tears has been shown to exist up to 8 years after the index ACL injury [43–46]. Frobell et al. reported a high prevalence of cortical depression fractures associated with larger PTBMLs and hypothesized this may have been produced by the articular cartilage and subchondral bone experiencing high magnitudes of compressive and shear stress at the time of ACL disruption [47]. These larger PTBMLs are primarily located in the lateral compartment [47, 48]. The presence of PTBML can help indicate the overall mechanism of injury, showing where the joint surface experienced significant compressive and shear forces from the impact of loading at the time of ACL disruption [1, 38]. The large magnitudes of compressive and shear forces transmitted across the tibiofemoral joint at the time of ACL injury have the potential to harm the articular and meniscal cartilage leading to cartilage matrix disruption, accelerated chondrocyte senescence, chondrocyte death, and cell metabolism changes [1, 49, 50]. In addition, Coughlin et al. proposed that bone–cartilage crosstalk, via molecular signaling, changes after a PTBML with subsequent increases in bone remodeling [51]. Changes in the bone–cartilage crosstalk may result in damage to the cartilage and is a potential mechanism for progression to PTOA [51].

A series of studies have found evidence linking PTBMLs with longitudinal cartilage damage. For example, Koster et al. reported bone marrow edema after knee trauma was a strong predictor of PTOA changes to the tibiofemoral joint at 1 year follow-up [52]. Theologis et al. reported the cartilage overlying bone marrow edema-like lesions in the lateral tibia had elevated T1ρ times at 1 year follow-up [53]. Similarly, Gong et al. reported that bone marrow edema-like lesions following ACL injury were associated with higher T1ρ and T2 relaxation times at 2 year follow-up, indicating worse cartilage health [54]. These cartilage changes remained present even after the bone marrow edema-like lesions had resolved, suggesting that damage to cartilage overlying PTBMLs may be irreversible [53, 54]. Although most PTBMLs resolve within 2 years after ACL injury, Frobell et al. theorized the high magnitudes of compressive and shear forces sustained by the bone and cartilage at the time of ACL injury, as indicated by a PTBML, could initiate biological developments that lead to PTOA in the long term [55]. Evidence suggests that PTBMLs may have a significant role in the mechanism of onset and progression of PTOA following ACL injury. As such, efforts to diagnose and study them in conjunction with ACL injuries and PTOA will be important in future research.

3.5 Effect of ACL Disruption and Concomitant Meniscal Injury on PTOA

Concomitant meniscal damage at the time of ACL injury significantly increases the risk of developing PTOA in the future, particularly in patients that undergo meniscectomy [11, 14, 21, 36, 56–59]. Oiestad et al. reported the prevalence of PTOA ranged from 21 to 48% in those with meniscal injuries compared with 0–13% in those with isolated ACL injuries without meniscal injuries 10 years after the index trauma [58]. In a subsequent study, Oiestad et al. reported 80% of subjects with PTOA had combined meniscal and ACL injuries compared with 62% of subjects with isolated ACL injuries at 10–15 years follow-up; however, there was no significant difference between the groups in terms of their functions and symptoms [60]. Further, after 20 years, PTOA was found in 81% of patients who underwent meniscectomy combined with ACL injury compared with 54% of those who only had isolated ACL injury [18].

Spindler et al. and Jones et al. have revealed that meniscal damage at the time of ACL injury is a risk factor for the development of PTOA and is also associated with worse results and patient-reported outcomes at 2- and 6-year follow-up intervals [12, 13]. This is a concern because the frequency and location of meniscus injury seen at the time of ACL reconstruction are associated with the patient sex, age, and surgical delay [35]. Slauterbeck et al. reported that at the time of ACL reconstruction, females are less likely to have a meniscus injury (56% compared with 71% for males), while males are more likely to have combined medial and lateral meniscus injuries (20% compared with 11% for females) [35]. Subjects with a delay between injury and ACL reconstructive surgery <3 months are least likely to have medial meniscus injury in comparison to those with a delay >3 months, and for subjects that are >35 years of age at the time of ACL reconstruction, meniscus injuries are more frequent and are more likely to occur in the medial compartment of the knee [35].

Many mechanisms are hypothesized to be associated with the increased rates of PTOA experienced by subjects that suffer an ACL injury with concomitant meniscal injury. An ACL-injured knee that has altered meniscus function has different gait patterns, increased magnitude of shear and compressive contact stresses during weight-bearing activity, cartilage proteoglycan changes, and increased fatigue, which combine to lead to progressive destruction of the collagen network [7]. At 10–15 year follow-up, greater deficits in quadriceps muscle strength were found in those with combined ACL and meniscal injury and/or chondral lesion compared with those with isolated ACL injuries [60]. Inferior cartilage proteoglycan content indicated by lower T1Gd was found with concomitant meniscectomy in the chronic phase after ACL injury [7]. Because meniscus damage is associated with higher risk of PTOA, many researchers have suggested repairing or preserving the meniscus as much as possible could be beneficial to the long-term health of the knee [2, 14, 34, 36, 57, 59].

Overall, concomitant meniscal injury increases the risk of inferior cartilage health; however, there is conflicting evidence in outcomes between ACL injury with concomitant medial versus lateral meniscus damage. Studies have reported that ACL injury in combination with lateral meniscus injury is associated with worse outcomes [1, 13], while other reports have linked ACL injury in combination with medial meniscus injury to worse outcomes [12, 61]. In addition, Jones et al. reported that a lateral meniscus tear and/or partial lateral meniscectomy were associated with better outcomes [12]. They hypothesized that this finding may be associated with the mechanism of injury, such that when the impact force is transmitted across the lateral compartment at the time of ACL causing lateral meniscus injury, the joint fares better than that if the force is transmitted elsewhere [12]. Jones et al. also reported that medial meniscus injury correlated with the medial compartment joint space narrowing 2–3 years after injury [12]. A systematic review of this area of inquiry reported a small increase in PTOA rates for ACL injury with concomitant medial meniscus injury, no increases for the same ligament trauma with concomitant lateral meniscus injury, but, overall, determined the current literature was based on a low level of evidence [61].

3.6 Effect of Surgical Versus Nonsurgical Treatment of ACL Injury on PTOA

Despite the availability of many different surgical treatment options for a disrupted ACL, a long-term protective effect of ACL reconstruction against the onset and progression of PTOA has not been established. Numerous studies have demonstrated that surgical reconstruction does not change the long-term outcomes, between 2 years and up to 20 years postoperatively, in PTOA symptoms, or function when compared to rehabilitation without reconstruction [1, 11, 18, 22, 56, 58, 62–64]. The knee anterior cruciate ligament, nonsurgical versus surgical treatment (KANON) randomized controlled trial demonstrated that the treatment of ACL injury with reconstruction compared to rehabilitation with optional delayed surgical reconstruction had no significant differences in patient-reported outcomes at 2 years and no significant differences in patient-reported outcomes and radiographic evidence of PTOA at 5-year follow-up [62, 63]. An important limitation of the KANON trial is the transfer bias at 5-year follow-up, where 51% of those in the rehabilitation with optional delayed surgery treatment arm of the study chose to undergo ACL reconstruction surgery as time post injury progressed [63]. This high transfer rate may have introduced bias into the study. However, the study by Frobell et al. [62, 63] is the only clinical trail the authors could identify that has the capacity to provide insight into the efficacy of surgical versus nonsurgical treatment of ACL injury. In contrast to the findings of numerous studies, one meta-analysis reported that ACL reconstruction had a lower RR of PTOA than nonoperative treatment at a mean follow-up of 10 years; however, they also found that ACL reconstruction had a higher proportion of moderate/severe PTOA than the nonoperative group [10]. One possible explanation the authors provided for this finding was the differences in patient expectations and activity modifications between the reconstruction versus nonsurgical treatment groups [10]. Also, this meta-analysis only included studies that used radiographic-based Kellgren and Lawrence classification of PTOA, potentially excluding the findings from studies that used more sensitive MRI-based PTOA classification systems [10].

Even though the choice to undergo ACL reconstruction or nonsurgical treatment does not appear to impact long-term outcomes, reconstruction versus rehabilitation with nonsurgical treatment appears to undergo different biomechanical and biological responses. Surgical reconstruction creates additional trauma to the joint with a prolonged elevation of the inflammatory response after the initial injury [1, 65]. For example, treatment of ACL injury with reconstruction results in higher cytokine levels compared with nonsurgical treatment with rehabilitation, with enduring elevations of synovial fluid IL-6 and TNF that activate MMPs and aggrecanases, increase proteolytic degradation, and decrease the synthesis of aggrecan and type II collagen [65]. In addition, structural changes associated with reconstruction have been noted, with increased radiographic changes in the patellofemoral joint and subchondral bone surface curvature [22, 66]. ACL reconstruction has also been associated with larger BMLs at 6 months compared with the treatment with rehabilitation alone; however, at 12 months, no differences in BMLs between surgical versus nonsurgical treatments were present [67].

Although ACL reconstruction has a significant impact on the knee, treatment with rehabilitation alone has an important impact that should be appreciated. ACL-deficient knees undergo biomechanical changes that have the potential to impact other knee structures including the menisci and cartilage. For example, the rate of meniscal injuries increases in ACL-deficient knees over time [1, 2, 11, 57, 68]. In addition, studies have examined how the biochemical environment of the knee changes following an ACL injury. Chinzei et al. reported that untreated ACL tears leave remnants of the torn ACL in the joint that may release mediators which affect cartilage metabolism, leading them to suggest that unreconstructed tears are not completely benign and may influence cartilage homeostasis [69].

3.7 Effect of Timing of ACL Reconstruction Surgery on PTOA

Risk for meniscal injury could be an indication for ACL reconstruction and the time frame for the surgery, because the longer the knee is ACL-deficient, the risk of developing meniscal injuries increases. Early reconstruction, <3–6 months after injury, appears to be associated with a decreased rate of meniscal injuries and meniscal surgeries including meniscectomies [1, 2, 11, 35]. These findings suggest that the timing of reconstruction is important. Barenius et al. reported that patients undergoing early reconstruction (<6 months after the ACL injury) had higher health-related quality of life at 8 years [11]. In addition, Slauterbeck et al. reported patients undergoing ACL reconstruction with a surgical delay of >1 year were more likely to have an articular cartilage lesion (60% compared with 47% with a delay <1 year), and a surgical delay of ACL reconstruction >1 year resulted in a greater proportion of large and grade 3 lesions of the lateral femoral condyle [35]. However, early ACL reconstruction also produced higher inflammatory cytokines for a longer period than rehabilitation plus optional delayed reconstruction, suggesting that delaying reconstruction could have beneficial effects on the temporal inflammatory process of the injured knee [65]. Another study reported a shorter surgical delay was correlated with a slower cartilage recovery after running, which may be an important factor to consider in high-demand athletes [70]. In contrast, other studies present evidence that early versus delayed reconstruction does not have a significant effect on patient outcomes. Studies have not found a difference between partial or full meniscectomy and meniscal repair surgery rates from 5 to 20 years between early reconstruction versus rehabilitation alone with optional delayed reconstruction [18, 63]. These findings challenge the premise that ACL-deficient knees are at increased risk for meniscal injuries. Hunter et al. found that time from injury to surgery had no effect on bone curvature change seen after reconstruction, an outcome thought to reflect bone remodeling and early onset of PTOA [66]. In addition, other evidence suggests the time between injury and reconstruction is not a risk factor for OA and does not influence its development [11, 61]. Frobell et al. suggest there is no difference in PTOA rates between early reconstruction compared to delayed reconstruction 5 years following an ACL tear; however, it is important to note this study was not designed to directly assess the timing of surgery [63]. Overall, the literature remains unclear on whether the timing of reconstruction surgery has an impact on the risk of developing PTOA.

3.8 Effect of ACL Graft Material on PTOA

The graft material used to reconstruct the ACL is an important concern that impacts knee health and long-term outcomes; however, the effect of the graft material used to reconstruct the ACL on the risk of developing PTOA is unclear. A series of studies have reported that ACL reconstruction with a bone–patellar tendon–bone (BPTB) autograft results in a higher prevalence of PTOA in comparison to reconstruction with hamstring tendon autografts over an average of 2–10 and 18–20 year follow-up intervals [71–73]. Keays et al. reported that BPTB grafts had higher rates of tibiofemoral

OA than hamstring tendon grafts; however, the authors did not indicate if autografts were used [36]. BPTB autografts are often associated with patellofemoral issues such as pain when walking on hard ground, kneeling, and numbness of skin, usually due to donor site morbidity [2, 11, 74]. Despite the high levels of OA with BPTB autografts, they have demonstrated satisfactory outcomes at long-term follow-up with improvement in function compared to preinjury levels [2, 72]. However, these studies investigating BPTB autografts versus hamstring tendon autografts were only able to establish associations and not cause-and-effect relationships. In contrast, a few studies with a higher level of evidence found no difference in outcomes between BPTB or hamstring grafts. Two randomized controlled trials found no differences in PTOA rates after 10–14 years between BPTB or hamstring tendon autografts [11, 75]. Similarly, a cohort study, while finding higher rates of PTOA in patients reconstructed with BPTB autografts compared with hamstring tendon autografts, found equivalent long-term clinical outcomes between the graft types 20 years postoperatively [73]. Likewise, a meta-analysis by Xie et al. reported a slight increase in OA rates for BPTB autografts compared with hamstring tendon autografts at a minimum of 5 years, although they cautioned the significance of this result due to the overall heterogeneity of findings and differences in classifications of PTOA used between the studies included in the analysis [74].

Another area of inquiry is whether the use of autografts versus allografts to reconstruct the ACL has an impact on knee health, as allografts would theoretically avoid problems with donor site morbidity. Jones et al. found the reconstruction of the ACL with allografts to be a risk factor for worse patient-reported outcomes 2–6 years postoperatively, and Amano et al. reported the use of allograft was associated with elevated T1ρ and T2 times, indicating worse cartilage health 3 years postoperatively [12, 15]. In contrast, one case–control study of BPTB grafts found no significant differences in PTOA between auto and allografts at 3–13 years follow-up in high-activity level patients; however, this study had a small sample size, it used a retrospective study design, and did provide an a priori power analysis [76]. Overall, there does not appear to be a consensus in the literature on the effect of the type of graft material on long-term development of PTOA.

3.9 Effect of ACL Trauma on Patellofemoral and Tibiofemoral PTOA

Following ACL trauma, it is unclear if the pathoetiology of the PTOA disease process is different between the tibiofemoral and patellofemoral joints. For example, 5 years following an index ACL injury, Frobell et al. revealed that 12% of ACL-injured knees had tibiofemoral OA and 20% had patellofemoral OA, irrespective of the surgical or nonsurgical treatment of the torn ligament [63]. In addition, they observed that patellofemoral OA was more common with BPTB autografts than hamstring tendon autografts [63]. The authors hypothesized this may have been produced by the surgical trauma associated with harvesting the BPTB graft, altered biomechanics of the patellofemoral joint caused by postoperative change of the patella and patellar tendon geometry, bony remodeling response of the patella, or some combination of these mechanisms [63]. In contrast, Risberg et al. studied subjects that underwent ACL reconstruction with either BPTB or hamstring tendon autografts and revealed the prevalence of radiographic tibiofemoral and patellofemoral PTOA rates were 42% and 21%, correspondingly, 20 years postoperatively [34]. However, 25% and 14% had symptomatic tibiofemoral and patellofemoral PTOA, respectively [34]. Culvenor et al. conducted a systematic review and reported that the prevalence of PTOA was similar between patellofemoral and tibiofemoral joints at 0–5, 5–10, and 10–15 years following ACL reconstruction [77].

3.10 Return to Sport Considerations for Athletes

The heterogeneity of findings on the efficacy of having reconstruction with early or delayed surgery poses a challenge, especially for high-level athletes. Overall, regardless of the treatment courses in athletes, ACL injury increases the risk of OA in the long term [18]. However, high-level athletes have significant demands placed on their knees that often differ remarkably from the general population. As such, the findings from studies whose subject population is not from elite athletics may not be generalizable to active individuals. The KANON trial by Frobell et al. demonstrated no difference in outcomes following ACL injury between treatment with reconstruction or rehabilitation alone and explicitly stated that their results do not apply to professional athletes [63]. Research that directly studies athletes may have more relevant findings. One study of 19 Olympic-level athletes from the 1960s with ACL injuries that did not undergo reconstruction reported that when these athletes returned to high-level activity, there was a 95% prevalence of meniscal and cartilage damage, osteoarthritis, instability, and severe symptoms after 20 years [78]. In addition, there was a 95% meniscectomy rate after 20 years and a 50% rate of total knee replacement after 35 years [78]. In elite soccer and alpine skiing athletes returning to their pre-injury sport, Hoffelner et al. found reconstruction did not increase the risk of PTOA, leading them to recommend that athletes returning to high-level sport undergo reconstruction [79]. Another study of high-level athletes found the treatment course did not affect PTOA rates, meniscectomy rates, and functional outcomes after 20 years and that the rates of PTOA in operatively treated athletes were 80% at 20 years [18]; however, these authors did report the reconstruction group had better knee stability [18].

To minimize risk from reconstruction due to the significant amount of acute changes it causes, it may be advisable to have extended recovery time after reconstruction and not rush back into sport [6, 67]. Van Ginckel et al. found cartilage showed decreased resiliency 6 months after surgery, with slower recovery of cartilage morphological characteristics after a running test [70]. This delayed cartilage recovery might cause maintained deformation and increased permeability of the articular cartilage [70]. As a result, the high-impact loading associated with participation in sports may lead to degeneration in these delayed recovery states [70]. These findings led Van Ginckel et al. to recommend that it may be important to consider a delayed RTS while cartilage is more fragile in the early phases after injury [70]. Culvenor et al. studied the impact of accelerated RTS after ACL reconstruction and found significantly greater odds of BMLs in those who returned to sport <10 months after reconstruction compared with those who did not return before 10 months [80]. These authors were unable to determine if these BMLs were new or persisted from the injury/surgery, but they theorized this may be a potential marker of early PTOA and an important factor to consider in RTS decisions [80].

It is important to note that athletes can RTS without the fear of guaranteeing worse outcomes in the long term. Oiestad et al. found patients who returned to planting, cutting, and pivoting sports had lower risk of symptomatic and radiographic PTOA at 15 years than those who did not return [81]. Keays et al. also found returning to sport did not increase the risk of PTOA [36]. These studies [36, 81] were not designed to establish the cause-and-effect relationships and can only show associations. Even though it is unclear whether RTS is due to confounding factors such as higher baseline knee function, results suggest for those with adequate knee function in the early phase, return to pivoting sport may not harm long-term knee health [81].

3.11 Limitations of the Current Literature

The complexity and insidious nature of PTOA has posed serious challenges for research. Very few RCTs have been designed to establish the mechanistic cause-and-effect relationship between severe knee trauma that involves disruption of the ACL to the onset and progression of PTOA. As such, very few conclusions on the cause-and-effect relationships can be made. There are many classification systems for PTOA, making it hard to compare the findings of studies that used different classifications. Also, because of the long-term nature associated with the development of PTOA, studies often take years if not decades to complete. As a result, the surgical and rehabilitation techniques used in studies may often become outdated, limiting the generalizability of the findings to current clinical practice. In addition, many studies have had heterogeneous results and relatively small sample sizes, making it hard to make overall inferences and limiting their applicability. Studies usually have an over-representation of males [10], and findings from these samples may not be suitable to the disease processes that occur in females. Similarly, samples often do not adequately represent elite athlete populations. Because athletes have significant differences in strengths and demands placed on their lower extremities compared with the general population, findings from studies that focus on the general population may not apply to elite athletes. More research is needed to assess the unique factors that affect the PTOA process in athletes.

References

1. Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. Am J Sports Med. 2007;35(10):1756–69. https://doi.org/10.1177/0363546507307396.
2. Ahn JH, Kim JG, Wang JH, Jung CH, Lim HC. Long-term results of anterior cruciate ligament reconstruction using bone-patellar tendon-bone: an analysis of the factors affecting the development of osteoarthritis. Arthroscopy. 2012;28(8):1114–23. https://doi.org/10.1016/j.arthro.2011.12.019.
3. Pedoia V, Su F, Amano K, Li Q, McCulloch CE, Souza RB, et al. Analysis of the articular cartilage T1rho and T2 relaxation times changes after ACL reconstruction in injured and contralateral knees and relationships with bone shape. J Orthop Res. 2017;35(3):707–17. https://doi.org/10.1002/jor.23398.
4. Williams A, Winalski CS, Chu CR. Early articular cartilage MRI T2 changes after anterior cruciate ligament reconstruction correlate with later changes in T2 and cartilage thickness. J Orthop Res. 2017;35(3):699–706. https://doi.org/10.1002/jor.23358.
5. Chen E, Amano K, Pedoia V, Souza RB, Ma CB, Li X. Longitudinal analysis of tibiofemoral cartilage contact area and position in ACL reconstructed patients. J Orthop Res. 2018;36(10):2718–27. https://doi.org/10.1002/jor.24024.
6. Van Ginckel A, Verdonk P, Witvrouw E. Cartilage adaptation after anterior cruciate ligament injury and reconstruction: implications for clinical management and research? A systematic review of longitudinal MRI studies. Osteoarthr Cartil. 2013;21(8):1009–24. https://doi.org/10.1016/j.joca.2013.04.015.
7. Neuman P, Tjornstrand J, Svensson J, Ragnarsson C, Roos H, Englund M, et al. Longitudinal assessment of femoral knee cartilage quality using contrast enhanced MRI (dGEMRIC) in patients with anterior cruciate ligament injury--comparison with asymptomatic volunteers. Osteoarthr Cartil. 2011;19(8):977–83. https://doi.org/10.1016/j.joca.2011.05.002.
8. Lonza GC, Gardner-Morse MG, Vacek PM, Beynnon BD. Radiographic-based measurement of tibiofemoral joint space width and magnetic resonance imaging derived articular cartilage thickness are not related in subjects at risk for post traumatic arthritis of the knee. J Orthop Res. 2019;37(5):1052–8. https://doi.org/10.1002/jor.24283.
9. Anderson DD, Chubinskaya S, Guilak F, Martin JA, Oegema TR, Olson SA, et al. Post-traumatic osteoarthritis: improved understanding and opportunities for early intervention. J Orthop Res. 2011;29(6):802–9. https://doi.org/10.1002/jor.21359.
10. Ajuied A, Wong F, Smith C, Norris M, Earnshaw P, Back D, et al. Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. Am J Sports Med. 2014;42(9):2242–52. https://doi.org/10.1177/0363546513508376.
11. Barenius B, Ponzer S, Shalabi A, Bujak R, Norlen L, Eriksson K. Increased risk of osteoarthritis after anterior cruciate ligament reconstruction: a 14-year follow-up study of a randomized controlled trial. Am J Sports Med. 2014;42(5):1049–57. https://doi.org/10.1177/0363546514526139.
12. Jones MH, Spindler KP. Risk factors for radiographic joint space narrowing and patient reported outcomes of post-traumatic osteoarthritis after ACL reconstruction: data from the MOON cohort. J Orthop Res. 2017;35(7):1366–74. https://doi.org/10.1002/jor.23557.
13. Spindler KP, Huston LJ, Chagin KM, Kattan MW, Reinke EK, Amendola A, et al. Ten-year outcomes and risk factors after anterior cruciate ligament reconstruction: a MOON longitudinal prospective cohort study. Am J Sports Med. 2018;46(4):815–25. https://doi.org/10.1177/0363546517749850.
14. Li RT, Lorenz S, Xu Y, Harner CD, Fu FH, Irrgang JJ. Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. Am J Sports Med. 2011;39(12):2595–603. https://doi.org/10.1177/0363546511424720.
15. Amano K, Huebner JL, Stabler TV, Tanaka M, McCulloch CE, Lobach I, et al. Synovial fluid profile at the time of anterior cruciate ligament reconstruction and its association with cartilage matrix composition 3 years after surgery. Am J Sports Med. 2018;46(4):890–9. https://doi.org/10.1177/0363546517749834.

16. Doherty M, Watt I, Dieppe P. Influence of primary generalised osteoarthritis on development of secondary osteoarthritis. Lancet. 1983;2(8340):8–11.
17. Englund M, Paradowski PT, Lohmander LS. Association of radiographic hand osteoarthritis with radiographic knee osteoarthritis after meniscectomy. Arthritis Rheum. 2004;50(2):469–75. https://doi.org/10.1002/art.20035.
18. van Yperen DT, Reijman M, van Es EM, Bierma-Zeinstra SMA, Meuffels DE. Twenty-year follow-up study comparing operative versus nonoperative treatment of anterior cruciate ligament ruptures in high-level athletes. Am J Sports Med. 2018;46(5):1129–36. https://doi.org/10.1177/0363546517751683.
19. Madaleno FO, Santos BA, Araujo VL, Oliveira VC, Resende RA. Prevalence of knee osteoarthritis in former athletes: a systematic review with meta-analysis. Braz J Phys Ther. 2018;22:437–51. https://doi.org/10.1016/j.bjpt.2018.03.012.
20. Driban JB, Hootman JM, Sitler MR, Harris KP, Cattano NM. Is participation in certain sports associated with knee osteoarthritis? A systematic review. J Athl Train. 2017;52(6):497–506. https://doi.org/10.4085/1062-6050-50.2.08.
21. Smith MV, Nepple JJ, Wright RW, Matava MJ, Brophy RH. Knee osteoarthritis is associated with previous meniscus and anterior cruciate ligament surgery among Elite College American football athletes. Sports Health. 2017;9(3):247–51. https://doi.org/10.1177/1941738116683146.
22. Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum. 2004;50(10):3145–52. https://doi.org/10.1002/art.20589.
23. von Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. Ann Rheum Dis. 2004;63(3):269–73.
24. Simon JE, Grooms DR, Docherty CL. The long term impact of osteoarthritis following knee surgery in former collegiate athletes. J Sport Rehabil. 2017:1–19. https://doi.org/10.1123/jsr.2017-0115.
25. Losina E, Weinstein AM, Reichmann WM, Burbine SA, Solomon DH, Daigle ME, et al. Lifetime risk and age at diagnosis of symptomatic knee osteoarthritis in the US. Arthritis Care Res. 2013;65(5):703–11. https://doi.org/10.1002/acr.21898.
26. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, part I. Am J Sports Med. 2005;33(10):1579–602. https://doi.org/10.1177/0363546505279913.
27. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, part 2. Am J Sports Med. 2005;33(11):1751–67. https://doi.org/10.1177/0363546505279922.
28. Bowers AL, Spindler KP, McCarty EC, Arrigain S. Height, weight, and BMI predict intra-articular injuries observed during ACL reconstruction: evaluation of 456 cases from a prospective ACL database. Clin J Sport Med. 2005;15(1):9–13.
29. Noyes FR, Bassett RW, Grood ES, Butler DL. Arthroscopy in acute traumatic hemarthrosis of the knee. Incidence of anterior cruciate tears and other injuries. J Bone Joint Surg. 1980;62(5):687–95, 757.
30. Piasecki DP, Spindler KP, Warren TA, Andrish JT, Parker RD. Intraarticular injuries associated with anterior cruciate ligament tear: findings at ligament reconstruction in high school and recreational athletes. An analysis of sex-based differences. Am J Sports Med. 2003;31(4):601–5. https://doi.org/10.1177/03635465030310042101.
31. Speer KP, Spritzer CE, Goldner JL, Garrett WE Jr. Magnetic resonance imaging of traumatic knee articular cartilage injuries. Am J Sports Med. 1991;19(4):396–402. https://doi.org/10.1177/036354659101900414.
32. Vellet AD, Marks PH, Fowler PJ, Munro TG. Occult posttraumatic osteochondral lesions of the knee: prevalence, classification, and short-term sequelae evaluated with MR imaging. Radiology. 1991;178(1):271–6. https://doi.org/10.1148/radiology.178.1.1984319.
33. Spindler KP, Wright RW. Clinical practice. Anterior cruciate ligament tear. N Engl J Med. 2008;359(20):2135–42. https://doi.org/10.1056/NEJMcp0804745.
34. Risberg MA, Oiestad BE, Gunderson R, Aune AK, Engebretsen L, Culvenor A, et al. Changes in knee osteoarthritis, symptoms, and function after anterior cruciate ligament reconstruction: a 20-year prospective follow-up study. Am J Sports Med. 2016;44(5):1215–24. https://doi.org/10.1177/0363546515626539.
35. Slauterbeck JR, Kousa P, Clifton BC, Naud S, Tourville TW, Johnson RJ, et al. Geographic mapping of meniscus and cartilage lesions associated with anterior cruciate ligament injuries. J Bone Joint Surg. 2009;91(9):2094–103. https://doi.org/10.2106/jbjs.H.00888.
36. Keays SL, Newcombe PA, Bullock-Saxton JE, Bullock MI, Keays AC. Factors involved in the development of osteoarthritis after anterior cruciate ligament surgery. Am J Sports Med. 2010;38(3):455–63. https://doi.org/10.1177/0363546509350914.
37. Argentieri EC, Sturnick DR, DeSarno MJ, Gardner-Morse MG, Slauterbeck JR, Johnson RJ, et al. Changes to the articular cartilage thickness profile of the tibia following anterior cruciate ligament injury. Osteoarthr Cartil. 2014;22(10):1453–60. https://doi.org/10.1016/j.joca.2014.06.025.
38. Owusu-Akyaw KA, Kim SY, Spritzer CE, Collins AT, Englander ZA, Utturkar GM, et al. Determination of the position of the knee at the time of an anterior cruciate ligament rupture for male versus female patients by an analysis of bone bruises. Am J Sports Med. 2018;46(7):1559–65. https://doi.org/10.1177/0363546518764681.
39. Lynch TC, Crues JV 3rd, Morgan FW, Sheehan WE, Harter LP, Ryu R. Bone abnormalities of the knee: prevalence and significance at MR imag-

ing. Radiology. 1989;171(3):761–6. https://doi.org/10.1148/radiology.171.3.2717748.
40. Newberg AH, Wetzner SM. Bone bruises: their patterns and significance. Semin Ultrasound CT MR. 1994;15(5):396–409.
41. Eustace S, Keogh C, Blake M, Ward RJ, Oder PD, Dimasi M. MR imaging of bone oedema: mechanisms and interpretation. Clin Radiol. 2001;56(1):4–12. https://doi.org/10.1053/crad.2000.0585.
42. Sievanen H, Kannus P, Heinonen A, Oja P, Vuori I. Bone mineral density and muscle strength of lower extremities after long-term strength training, subsequent knee ligament injury and rehabilitation: a unique 2-year follow-up of a 26-year-old female student. Bone. 1994;15(1):85–90.
43. Kannus P, Sievanen H, Jarvinen M, Heinonen A, Oja P, Vuori I. A cruciate ligament injury produces considerable, permanent osteoporosis in the affected knee. J Bone Miner Res. 1992;7(12):1429–34. https://doi.org/10.1002/jbmr.5650071210.
44. van Meer BL, Oei EH, Bierma-Zeinstra SM, van Arkel ER, Verhaar JA, Reijman M, et al. Are magnetic resonance imaging recovery and laxity improvement possible after anterior cruciate ligament rupture in nonoperative treatment? Arthroscopy. 2014;30(9):1092–9. https://doi.org/10.1016/j.arthro.2014.04.098.
45. Bayar A, Sarikaya S, Keser S, Ozdolap S, Tuncay I, Ege A. Regional bone density changes in anterior cruciate ligament deficient knees: a DEXA study. Knee. 2008;15(5):373–7. https://doi.org/10.1016/j.knee.2008.05.005.
46. Nyland J, Fisher B, Brand E, Krupp R, Caborn DN. Osseous deficits after anterior cruciate ligament injury and reconstruction: a systematic literature review with suggestions to improve osseous homeostasis. Arthroscopy. 2010;26(9):1248–57. https://doi.org/10.1016/j.arthro.2010.03.017.
47. Frobell RB, Roos HP, Roos EM, Hellio Le Graverand MP, Buck R, Tamez-Pena J, et al. The acutely ACL injured knee assessed by MRI: are large volume traumatic bone marrow lesions a sign of severe compression injury? Osteoarthr Cartil. 2008;16(7):829–36. https://doi.org/10.1016/j.joca.2007.11.003.
48. Papalia R, Torre G, Vasta S, Zampogna B, Pedersen DR, Denaro V, et al. Bone bruises in anterior cruciate ligament injured knee and long-term outcomes. A review of the evidence. Open Access J Sports Med. 2015;6:37–48. https://doi.org/10.2147/oajsm.S75345.
49. Li H, Chen C, Chen S. Posttraumatic knee osteoarthritis following anterior cruciate ligament injury: potential biochemical mediators of degenerative alteration and specific biochemical markers. Biomed Rep. 2015;3(2):147–51. https://doi.org/10.3892/br.2014.404.
50. Struglics A, Okroj M, Sward P, Frobell R, Saxne T, Lohmander LS, et al. The complement system is activated in synovial fluid from subjects with knee injury and from patients with osteoarthritis. Arthritis Res Ther. 2016;18(1):223. https://doi.org/10.1186/s13075-016-1123-x.
51. Coughlin TR, Kennedy OD. The role of subchondral bone damage in post-traumatic osteoarthritis. Ann N Y Acad Sci. 2016;1383(1):58–66. https://doi.org/10.1111/nyas.13261.
52. Koster IM, Oei EH, Hensen JH, Boks SS, Koes BW, Vroegindeweij D, et al. Predictive factors for new onset or progression of knee osteoarthritis one year after trauma: MRI follow-up in general practice. Eur Radiol. 2011;21(7):1509–16. https://doi.org/10.1007/s00330-011-2089-3.
53. Theologis AA, Kuo D, Cheng J, Bolbos RI, Carballido-Gamio J, Ma CB, et al. Evaluation of bone bruises and associated cartilage in anterior cruciate ligament-injured and -reconstructed knees using quantitative t(1rho) magnetic resonance imaging: 1-year cohort study. Arthroscopy. 2011;27(1):65–76. https://doi.org/10.1016/j.arthro.2010.06.026.
54. Gong J, Pedoia V, Facchetti L, Link TM, Ma CB, Li X. Bone marrow edema-like lesions (BMELs) are associated with higher T1rho and T2 values of cartilage in anterior cruciate ligament (ACL)-reconstructed knees: a longitudinal study. Quant Imaging Med Surg. 2016;6(6):661–70. https://doi.org/10.21037/qims.2016.12.11.
55. Frobell RB. Change in cartilage thickness, posttraumatic bone marrow lesions, and joint fluid volumes after acute ACL disruption: a two-year prospective MRI study of sixty-one subjects. J Bone Joint Surg. 2011;93(12):1096–103. https://doi.org/10.2106/jbjs.J.00929.
56. Nordenvall R, Bahmanyar S, Adami J, Mattila VM, Fellander-Tsai L. Cruciate ligament reconstruction and risk of knee osteoarthritis: the association between cruciate ligament injury and post-traumatic osteoarthritis. a population based nationwide study in Sweden, 1987-2009. PLoS One. 2014;9(8):e104681. https://doi.org/10.1371/journal.pone.0104681.
57. Magnussen RA, Duthon V, Servien E, Neyret P. Anterior cruciate ligament reconstruction and osteoarthritis: evidence from long-term follow-up and potential solutions. Cartilage. 2013;4(3 Suppl):22s–6s. https://doi.org/10.1177/1947603513486559.
58. Oiestad BE, Engebretsen L, Storheim K, Risberg MA. Knee osteoarthritis after anterior cruciate ligament injury: a systematic review. Am J Sports Med. 2009;37(7):1434–43. https://doi.org/10.1177/0363546509338827.
59. Claes S, Hermie L, Verdonk R, Bellemans J, Verdonk P. Is osteoarthritis an inevitable consequence of anterior cruciate ligament reconstruction? A meta-analysis. Knee Surg Sports Traumatol Arthrosc. 2013;21(9):1967–76. https://doi.org/10.1007/s00167-012-2251-8.

60. Oiestad BE, Holm I, Aune AK, Gunderson R, Myklebust G, Engebretsen L, et al. Knee function and prevalence of knee osteoarthritis after anterior cruciate ligament reconstruction: a prospective study with 10 to 15 years of follow-up. Am J Sports Med. 2010;38(11):2201–10. https://doi.org/10.1177/0363546510373876.
61. van Meer BL, Meuffels DE, van Eijsden WA, Verhaar JA, Bierma-Zeinstra SM, Reijman M. Which determinants predict tibiofemoral and patellofemoral osteoarthritis after anterior cruciate ligament injury? A systematic review. Br J Sports Med. 2015;49(15):975–83. https://doi.org/10.1136/bjsports-2013-093258.
62. Frobell RB, Roos EM, Roos HP, Ranstam J, Lohmander LS. A randomized trial of treatment for acute anterior cruciate ligament tears. N Engl J Med. 2010;363(4):331–42. https://doi.org/10.1056/NEJMoa0907797.
63. Frobell RB, Roos HP, Roos EM, Roemer FW, Ranstam J, Lohmander LS. Treatment for acute anterior cruciate ligament tear: five year outcome of randomised trial. BMJ. 2013;346:f232. https://doi.org/10.1136/bmj.f232.
64. Meuffels DE, Favejee MM, Vissers MM, Heijboer MP, Reijman M, Verhaar JA. Ten year follow-up study comparing conservative versus operative treatment of anterior cruciate ligament ruptures. A matched-pair analysis of high level athletes. Br J Sports Med. 2009;43(5):347–51. https://doi.org/10.1136/bjsm.2008.049403.
65. Larsson S, Struglics A, Lohmander LS, Frobell R. Surgical reconstruction of ruptured anterior cruciate ligament prolongs trauma-induced increase of inflammatory cytokines in synovial fluid: an exploratory analysis in the KANON trial. Osteoarthr Cartil. 2017;25(9):1443–51. https://doi.org/10.1016/j.joca.2017.05.009.
66. Hunter DJ, Lohmander LS, Makovey J, Tamez-Pena J, Totterman S, Schreyer E, et al. The effect of anterior cruciate ligament injury on bone curvature: exploratory analysis in the KANON trial. Osteoarthr Cartil. 2014;22(7):959–68. https://doi.org/10.1016/j.joca.2014.05.014.
67. Frobell RB, Le Graverand MP, Buck R, Roos EM, Roos HP, Tamez-Pena J, et al. The acutely ACL injured knee assessed by MRI: changes in joint fluid, bone marrow lesions, and cartilage during the first year. Osteoarthr Cartil. 2009;17(2):161–7. https://doi.org/10.1016/j.joca.2008.06.020.
68. Fithian DC, Paxton EW, Stone ML, Luetzow WF, Csintalan RP, Phelan D, et al. Prospective trial of a treatment algorithm for the management of the anterior cruciate ligament-injured knee. Am J Sports Med. 2005;33(3):335–46. https://doi.org/10.1177/0363546504269590.
69. Chinzei N, Brophy RH, Duan X, Cai L, Nunley RM, Sandell LJ, et al. Molecular influence of anterior cruciate ligament tear remnants on chondrocytes: a biologic connection between injury and osteoarthritis. Osteoarthr Cartil. 2018;26(4):588–99. https://doi.org/10.1016/j.joca.2018.01.017.
70. Van Ginckel A, Verdonk P, Victor J, Witvrouw E. Cartilage status in relation to return to sports after anterior cruciate ligament reconstruction. Am J Sports Med. 2013;41(3):550–9. https://doi.org/10.1177/0363546512473568.
71. Mascarenhas R, Tranovich MJ, Kropf EJ, Fu FH, Harner CD. Bone-patellar tendon-bone autograft versus hamstring autograft anterior cruciate ligament reconstruction in the young athlete: a retrospective matched analysis with 2-10 year follow-up. Knee Surg Sports Traumatol Arthrosc. 2012; 20(8):1520–7. https://doi.org/10.1007/s00167-011-1735-2.
72. Ettinger M, Etter F, Calliess T, Bohnsack M, Becher C. Long term results of bone-patella-tendon-bone ACL reconstruction. J Orthop. 2017;14(1):91–4. https://doi.org/10.1016/j.jor.2016.10.027.
73. Thompson SM, Salmon LJ, Waller A, Linklater J, Roe JP, Pinczewski LA. Twenty-year outcome of a longitudinal prospective evaluation of isolated endoscopic anterior cruciate ligament reconstruction with patellar tendon or hamstring autograft. Am J Sports Med. 2016;44(12):3083–94. https://doi.org/10.1177/0363546516658041.
74. Xie X, Xiao Z, Li Q, Zhu B, Chen J, Chen H, et al. Increased incidence of osteoarthritis of knee joint after ACL reconstruction with bone-patellar tendon-bone autografts than hamstring autografts: a meta-analysis of 1,443 patients at a minimum of 5 years. Eur J Orthop Surg Traumatol. 2015;25(1):149–59. https://doi.org/10.1007/s00590-014-1459-3.
75. Holm I, Oiestad BE, Risberg MA, Aune AK. No difference in knee function or prevalence of osteoarthritis after reconstruction of the anterior cruciate ligament with 4-strand hamstring autograft versus patellar tendon-bone autograft: a randomized study with 10-year follow-up. Am J Sports Med. 2010;38(3):448–54. https://doi.org/10.1177/0363546509350301.
76. Mascarenhas R, Tranovich M, Karpie JC, Irrgang JJ, Fu FH, Harner CD. Patellar tendon anterior cruciate ligament reconstruction in the high-demand patient: evaluation of autograft versus allograft reconstruction. Arthroscopy. 2010;26(9 Suppl):S58–66. https://doi.org/10.1016/j.arthro.2010.01.004.
77. Culvenor AG, Cook JL, Collins NJ, Crossley KM. Is patellofemoral joint osteoarthritis an under-recognised outcome of anterior cruciate ligament reconstruction? A narrative literature review. Br J Sports Med. 2013;47(2):66–70. https://doi.org/10.1136/bjsports-2012-091490.
78. Nebelung W, Wuschech H. Thirty-five years of follow-up of anterior cruciate ligament-deficient knees in high-level athletes. Arthroscopy. 2005;21(6):696–702. https://doi.org/10.1016/j.arthro.2005.03.010.

79. Hoffelner T, Resch H, Moroder P, Atzwanger J, Wiplinger M, Hitzl W, et al. No increased occurrence of osteoarthritis after anterior cruciate ligament reconstruction after isolated anterior cruciate ligament injury in athletes. Arthroscopy. 2012;28(4):517–25. https://doi.org/10.1016/j.arthro.2011.09.014.
80. Culvenor AG, Patterson BE, Guermazi A, Morris HG, Whitehead TS, Crossley KM. Accelerated return to sport after anterior cruciate ligament reconstruction and early knee osteoarthritis features at 1 year: an exploratory study. PM R. 2018;10(4):349–56. https://doi.org/10.1016/j.pmrj.2017.09.005.
81. Oiestad BE, Holm I, Risberg MA. Return to pivoting sport after ACL reconstruction: association with osteoarthritis and knee function at the 15-year follow-up. Br J Sports Med. 2018;52(18):1199–204. https://doi.org/10.1136/bjsports-2017-097718.

Part II

Return to Sport: Whose Decision Is It?

4 Return to Sport Decision-Based Models

Ian Shrier

4.1 Introduction

Return to sport (RTS) decisions for any injury can be difficult and complex [1]. Clinicians and patients need to weigh a large number of factors when assessing RTS, including the history of the injury, physical examination, type of injury, rehabilitation, type of activity, psychological state, competitive level, and ability to protect the injury. Patients with anterior cruciate ligament (ACL) injuries have similar concerns as patients with other injuries, although some long-term consequences such as osteoarthritis might be more worrisome and therefore be considered as more important than a hamstring strain. Regardless of the injury, injured patients often ask, "When can I return to play?" or "When can I *safely* return to play?" In addition, the athlete may receive advice from family, friends, coaches, other clinicians, and, in the case of elite athletes, agents. Defining *safely* is subjective, and we will see that subjectivity should be embraced as part of an appropriate decision-making process.

Determining prognosis is difficult because we simply do not have adequate research. Therefore, some disagreements regarding RTS will always occur [2]. These differences are believed to lead to a number of negative scenarios, including (1) miscommunication, (2) loss of trust, (3) potential litigation, (4) declines in sport participation rates as some individuals never "get back in the game" due to fear of reinjury (despite acceptable levels of risk), and (5) even more serious medical complications, because some athletes return to activity while still at unacceptable levels of risk for subsequent sport-related injury [3–6].

Although two people may disagree on the importance of different factors, they should still be able to agree on the process by which RTS decisions are made. The process will depend on sociocultural perspectives, which may differ between the medical doctor, coach, and athlete and by region. For example, the current legal culture in many parts of North America has the medical doctor as the absolute authority. However, the recent movement towards shared decision-making in medicine could shift these norms so that athletes, otherwise capable of making autonomous decisions, are provided with the necessary information and take responsibility for their own choices. Regardless of the cultural context, RTS decisions should be based on a transparent framework in order to minimize any unnecessary conflict.

In this chapter, I review the Strategic Assessment of Risk and Risk Tolerance (StARRT) framework [7] for RTS decisions that was based on earlier work [8] and explain how it might fit into a more general framework of overall athlete care. The StARRT framework helps organize complex information; it should not be inter-

I. Shrier (✉)
Centre for Clinical Epidemiology, Jewish General Hospital, QC, Canada
e-mail: ian.shrier@mcgill.ca

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_4

preted as proscriptive. It is based on causal relationships and considers that differences in RTS decisions are partly due to differences in both risk assessment and risk tolerance. In validation studies, the framework is consistent with clinicians' beliefs independent of country of practice or clinician specialty [9]. One advantage of the framework is that differences in risk assessment could be decreased through the application of research and knowledge dissemination leading to improved evidence-based medicine. Additionally, the framework supports shared decision-making because it acknowledges that it is appropriate for two persons with different risk tolerances to come to different decisions based on the same factual information [10]. Finally, the framework's general approach means that it can be applied by whoever represents the decision-making authority: a clinician, non-clinician, or a multidisciplinary team.

4.2 Overall Athlete Care

The clinician's primary interest should be for the best interest of the athlete-patient. The patient operates within an ecosystem of other athletes, coaches, therapists, family, friends, and others. Because the interactions between these individuals is different for each patient and these interactions may affect the mental health or motivation of an injured athlete, the optimal treatment program for two athletes with the exact same pathology will differ. This biopsychosocial approach is gaining popularity in health settings [2, 11–13] and will likely become more common in future RTS decision-making processes.

In a recent consensus statement [14], biological, psychological, and social factors were all considered to influence rehabilitation outcomes and successful RTS. Several reports suggest that fear of reinjury (psychological) may delay RTS because the athlete is not mentally prepared [15]. Family stress may require athletes to prioritize other life responsibilities over rehabilitation. Because an effective rehabilitation or RTS program requires the athlete to follow the program, clinicians should strive to understand all the barriers that athletes may face and to think of facilitators that can help the athlete achieve their goals. Although the recent consensus statement was a good start, it was limited in its scope because it was focused only on the actual decision for RTS.

A more complete perspective is that RTS is a process which begins with a healthy athlete, where the clinician operates within an ecosystem and must understand how the different parts of the ecosystem interact. A healthy ecosystem would include transparent and clear roles for each person interacting with the athlete, recognizing that there is a natural overlap at different stages of the injury-healing continuum. In most contexts, athletes are treated by therapists until they are deemed healthy enough to compete, and then the care is transferred to the coaching staff. There might be some overlap where the athlete continues to receive some care after they return to sport, but for the most part, each profession acts independently.

As the Consulting Medical Director for Cirque du Soleil, I worked with the former Director of Performance Medicine, Jay Mellette, who is currently the Director of Sports Performance and Head Athletic Trainer of the Vegas Golden Knights, National Hockey League. Jay preferred to frame the issue so that clinicians are concerned with the athlete's health from the moment they become part of the organization and that they remain concerned about effects on health long after the athlete has left our care. He also believes that "integrated care" is the best model, where each relevant professional is involved throughout the care. For example, the lead at differing points in the process might be the coaching staff, the therapy staff, or the physician. Figure 4.1 is a representation of Jay's model which builds upon the consensus statement [14]. I have called it the FAIR (From Activity to Injury to Rehabilitation/Reintegration) model. The figure is simplified, showing only coaching staff and therapist, but it can easily be expanded in concept to include other health professionals, family, friends, and others.

Examining Fig. 4.1, we begin with the healthy athlete. We assume that all personnel are qualified and knowledgeable. Initially, the healthy athlete is mostly managed by the coach through workload management for training and competition because they have the most knowledge and

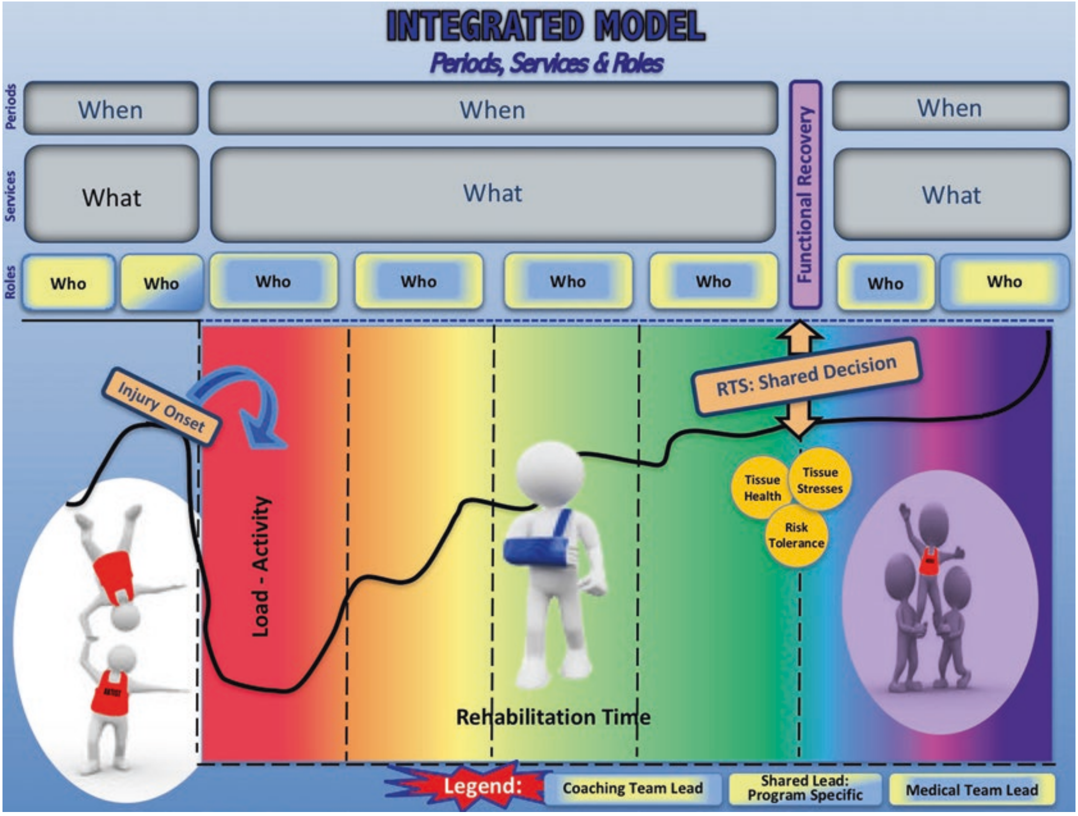


Fig. 4.1 The FAIR (From Activity to Injury to Rehabilitation/ Reintegration) model of athlete care. The relationship between the athlete, coach, and the health care team begins with a healthy athlete. During this time, the coaching staff is usually the lead in establishing training and competition workload to improve performance and minimize injury. The health care team provides a supporting role and addresses limitations identified through history and physical examination or through prevention programs directed at specific requirements of the position within the sport. At the time of injury, the coaching staff and health care team both contribute substantially in establishing appropriate workload and managing expectations. During the initial phase of rehabilitation, the health care team has more influence and the coaching staff provides the supporting role. As the athlete's injury heals, there is a gradual shift towards the coaching staff taking more responsibility and authority. In the post-injury phase, there is still some focus on prevention of reinjury, and the training returns towards the goal of optimizing performance and long-term health

experience. However, team therapists might be able to contribute with knowledge of specific injury prevention programs or identify athletes that might require specific exercises to overcome functional musculoskeletal deficits. Coordination is required between all personnel to manage the athlete's workload (1) because athlete's only have so much time in a day and (2) to mitigate deleterious effects on health and performance from the total stress summed across all activities.

In the period immediately after injury, the coaching and therapy staff continue to have shared roles with respect to determining ability to perform, role of rehabilitation, and managing athlete expectations. During the injury itself, the therapist takes care of the rehabilitation, but the coach is involved in managing global workloads and identifying ways to keep the athlete engaged with the team (e.g. reviewing videos, focused practice, and exercise programming that does not stress the injured tissue). As tissue strength improves, the athlete gains more function and the rehabilitation exercises gradually shift to performance-based exercises. Once the athlete is healthy, we return to the objectives of prevention and optimizing performance.

Throughout the timespan that the athlete is with the team or under care, considering the health of the athlete through the biopsychosocial model optimizes overall health and performance. RTS decisions through the StARRT framework represent one step, albeit a complex and important one, in the FAIR model.

4.3 StARRT Framework for RTS Decision-Making

The StARRT framework for RTS decisions is illustrated in Fig. 4.2. Rational decision-making requires weighing the benefits and risks of different alternatives [16–18]. For RTS decisions, the clinician is generally concerned with managing risk of reinjury, but may at times be concerned with risk of new injuries, death, or illness.

The StARRT model begins with a biomechanical causal framework; it assesses risk of injury by comparing how much stress the tissue can withstand (Tissue Health), with the stresses that are imposed by a prescribed level of activity (Tissue Stresses). Some of the factors may be known by the health care professional and some may be known by the coach. The source of the information is irrelevant from a theoretical perspective. That said, the fact there are several different sources of information underscores

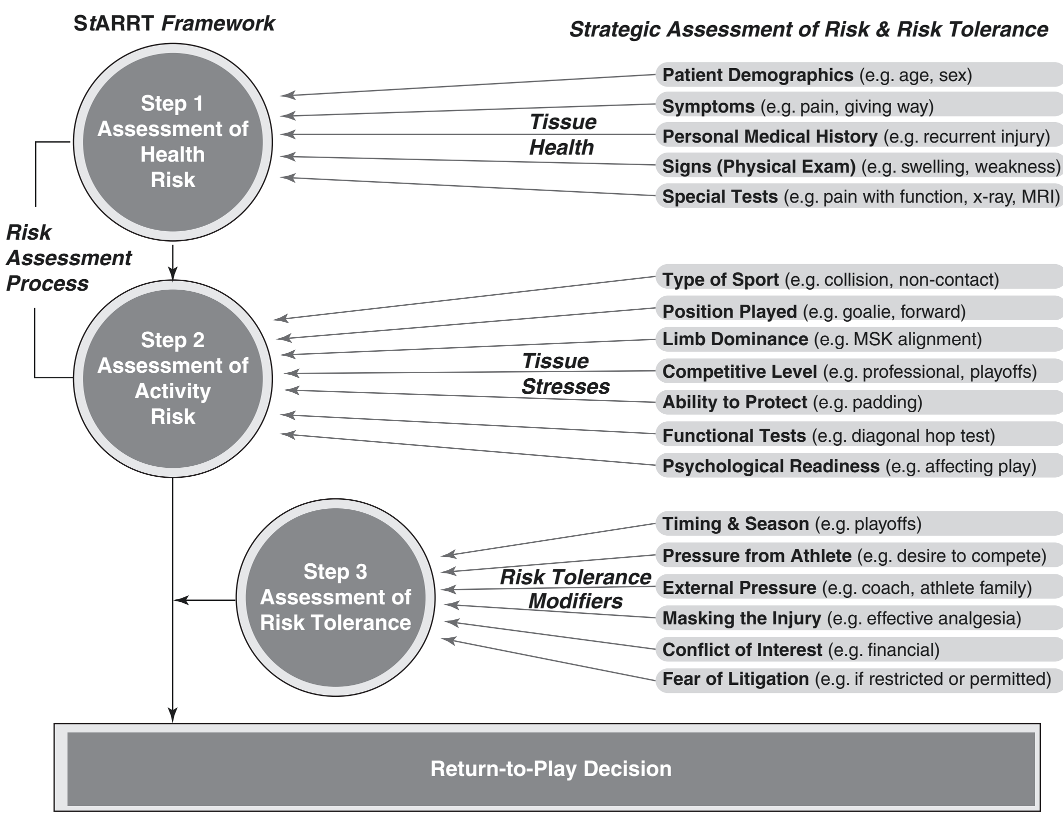


Fig. 4.2 The Strategic Assessment of Risk and Risk Tolerance (StARRT) framework for return to sport (RTS) decisions. This framework illustrates that athletes should be allowed to return to play when the risk assessment (Steps 1 and 2) is below the acceptable risk tolerance threshold (Step 3) and not allowed to return to play if the risk assessment is above the risk tolerance threshold. The StARRT framework groups factors according to their causal relationships with the two components of risk assessment (tissue health, stresses applied to tissue) and risk tolerance. In some cases, an apparently single factor can have more than one causal connection and would be repeated. For example, playoffs will increase the competitive level of play and therefore increase tissue stresses and increase risk. However, playoffs are also expected to affect an athlete's desire to compete (i.e. mood, risk of depression if not allowed to RTS) and could affect financial benefit as well. These causal effects would lead to increased risk tolerance. In the StARRT framework, each outcome is evaluated for RTS, and the overall decision is based on the most restricted activity across all outcomes (see text for details) (Reprinted from: Shrier [7])

the need for coordination and communication of care amongst all parties through the FAIR model mentioned above. To anchor the discussion, let us assume we are evaluating an athlete who had a complete ACL tear reconstructed with a bone-patellar-bone graft 4 months previously. We are asked to determine if the athlete can RTS.

4.3.1 Step 1: Tissue Health

According to the first step in Fig. 4.2, we need to assess the stress the tissue can absorb before becoming damaged. If the bone-bone interface of the new reconstruction remains weak, or the patella remains weak following the graft, the risk of injury will be much higher than if more time is allowed for healing. In general, we often evaluate the strength of injured tissues through the presence of symptoms (e.g. pain), signs (e.g. swelling), and diagnostic tests (e.g. muscle strength). Where we do not have good indicators of tissue health, we rely on our knowledge of healing from the basic sciences. It may not be great evidence, but it may be the best we have.

4.3.2 Step 2: Tissue Stresses

The objective at the end of Step 2 is to understand the risk of each important outcome (e.g. reinjury, osteoarthritis) for a given level of activity. Conceptually, there is a risk assessment for each of level of activity. As the level of activity increases, the stress applied to the tissue will be greater than the tissue can absorb and a reinjury would occur. Alternatively, the amount of stress to other body parts that are compensating might overwhelm the strength of those tissues and cause injury. Long-term effects might occur if the muscles are not able to absorb the normal shock that occurs across a joint [19].

Traditionally, training activity has been categorized using the “FITT” principle: one can modify activity through frequency (e.g. 3 day/week), intensity (e.g. running fast or climbing hills), timing (e.g. 20 min/session), and type. In the case of an ACL reconstruction, some activities such as flutter kick with swimming place only minimal stress on the ACL. Other activities such as high-level competitive table tennis require twisting and sudden motions at the knee, which may result in stresses that surpass the healing stage at 4 months. This emphasizes how the StARRT framework is based on the biomechanics that cause an increased stress (i.e. the causes of injury).

When thinking about RTS, clinicians should frame the discussion in terms of what activities provide stress levels that do not surpass the expected health of the tissue. In this sense, the answer for RTS in every case is Yes, and the decision is really about the definition of “activity/play” at that moment in time.

Although Fig. 4.2 includes specific categories under Step 1 and Step 2, these are conceptual and only to be used as guides to help decision-makers capture relevant information through a structured approach. For example, in a team relay in swimming, the decision to include breast-stroke (whip-kick) vs. crawl (flutter kick) as different sports or different positions within a sport is academic. Similarly, tight hamstrings in an athlete mean that forward flexion must come more from the back, which increases lumbar and thoracic stress and would be part of Step 2 if one were concerned about back injury. However, tight hamstrings might represent a sign of increased fatigue for the hamstrings, which is a sign of hamstring tissue weakness and part of Step 1 if one were concerned about hamstring injury.

4.3.3 Step 3: Risk Tolerance Modifiers

Once we have an idea of the risk, we then decide if the risk is acceptable. This is a key step in making the RTS process transparent. For the same absolute risk, two clinicians (or two athletes) may have different risk tolerances, and therefore come to different RTS decisions. In addition, a clinician evaluating an athlete with a sprained ankle who is about to compete in the Olympics versus a 14-year-old playing high school basketball understands from the biopsychosocial model that there are other aspects to life aside from the risk of reinjury. These other factors contribute to the athlete’s health and should affect our decision as to whether a particular risk is acceptable or not. A factor is included as a risk tolerance modifier if there is any context where changing the factor would change one's threshold of an acceptable risk.

The StARRT framework is about arriving at a decision based on whether the assessment of risk exceeds one's risk tolerance. In the FAIR model, we are concerned with the overall health or well-being of the athlete [20]. How do we define well-being or health? In a series of studies, we found that both sport medicine clinicians and non-clinicians considered psychological-related factors (desire to compete, psychological impact of not returning to play, loss of competitive standing) as well as potential financial loss, timing of the season, competitive level, and fear of litigation as important factors in their decisions [9]. Clinicians and non-clinicians had similar ratings across most of these factors [20].

The StARRT framework sits within the FAIR model of athlete care. It helps organize the information available into risk assessment (Steps 1 and 2) for a particular outcome and how to be aware of factors affecting one's risk tolerance for that outcome (Step 3). In the next section, we discuss how to apply the framework in some challenging situations.

4.4 A Concrete Example in Applying the StARRT Framework

Applying the StARRT framework should usually be straightforward. For this example, we will use an acromio-clavicular joint sprain in a collegiate American football linebacker because this was one of the clinical vignettes in our validation study (Fig. 4.3) [10].

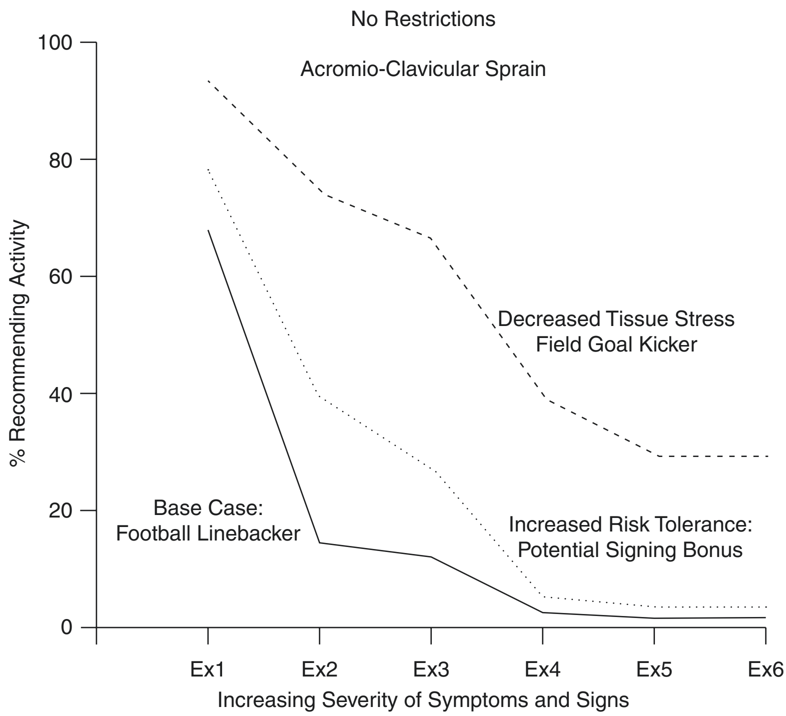


Fig. 4.3 The proportion of respondents who would allow activity without restriction is plotted for the different acromio-clavicular injury severity levels (increasing severity from Example 1 to Example 6) described in the clinical vignettes included in the validation study of Shrier et al. [10]. The *solid line* presents the results for the base case when the athlete is an American football linebacker. The *dashed line* presents the results when we decreased the likelihood of excessive stress by considering the player to be a field goal kicker instead of a linebacker (Tissue Stresses). The *dotted line* presents the results when the linebacker (base case) was being evaluated for a multi-million-dollar bonus (Risk Tolerance modifiers) (Reprinted from: Shrier [7])

The increase in signs and symptoms from Example 1 through Example 6 is due to an increase in tissue damage, which means the tissue will be less able to absorb stress before reinjury. As the tissue health decreased, clinicians were less likely to allow the athlete to full RTS. When we changed the scenario to a field goal kicker (very low risk of contact), we effectively decreased the stress that would be applied to the tissue (i.e. contact), the risk of reinjury decreased, and more clinicians were ready to allow the athlete to return to full activity. To see the importance of effect modifiers, we changed the vignette so that the athlete was being evaluated for a million-dollar signing bonus. At each level of risk of reinjury, clinicians followed the biopsychosocial model and realized that potential economic benefit contributes to overall health, and more clinicians allowed the athlete to RTS.

The example in this section discussed RTS decisions as if they are all or none. Alternatively, we could have placed different levels of activity on the x-axis (weight room only, running drills, full practice, full game) and asked clinicians whether they would let the injured athlete participate. For any one level of injury, more clinicians would let the athlete in the weight room, fewer would allow full practice, and even fewer would allow full game.

4.4.1 Multiple Outcomes

When we first proposed the StARRT framework, some had argued that the clinician should simply stop at Step 1 for life or limb-threatening conditions. However, there is a risk of death in every sport. For injured athletes, these critics seemed to be evaluating if the increased risk of death of the athlete in this context was "unacceptably greater" than the risk of death amongst the usual player (or the same player before the injury). However, this logic has important limitations.

To illustrate the limitations in the logic, let us consider a basketball player recovering from a concussion. On Day 5 post-concussion, the athlete has headaches after reading for 5 min. It is likely that most clinicians would not allow any practice or competition. What if we consider the same story, but in a table tennis player? We might believe table tennis is not a good idea because it would increase the symptoms, but we are no longer worried about an increased risk of death. This vignette illustrates that the level of activity is central to the RTS decision-making process because it is the piece we can control. We can almost always set the activity level so there is an "acceptable risk". From a different perspective, playing injured in one sport (e.g. baseball) may have less risk than playing healthy in another sport (e.g. American football). Therefore, to be internally consistent, we must evaluate the absolute risk for the athlete and not compare the risk with the risk of a healthy person in the same sport.

As noted above, some clinicians find the model easier to understand when used as a method to determine which level of activity is permissible, rather than thinking of RTS as an all-or-none decision. By separating out risk modifiers from assessment of risk, and then separating out the components that contribute to risk assessment, the StARRT framework helps make these formerly hidden assumptions more transparent for the clinician.

We have already mentioned how the StARRT framework can be used for any outcome – injury, death, and so on. The examples thus far have focused on one outcome. Because we are normally interested in many outcomes, the RTS decision is simply the most conservative decision from all the outcomes. In other words, the decision is "No" if the risk tolerance for any outcome is No. Alternatively, if we consider the RTS decision to determine the level of activity permitted, it is the highest level of activity that produces an acceptable level of risk across all outcomes. The logic is the same as an athlete with multiple injuries. If an athlete has an ankle injury that would allow her to run, but a knee injury that requires crutches, she is prescribed crutches.

Risk tolerance modifiers reflect contexts where risk tolerance is affected, but do not represent risks themselves. Sometimes a factor may affect the risk, and yet is also a risk modifier for different reasons. For example, play is often more aggressive during the playoffs compared to the early season, representing an increase in the stress applied to the tissue (Step 2). Playoff games may also affect risk tolerance (Step 3) because the financial compensation, psychological state, and prestige are different compared with the early season. The reason playoffs are considered in both steps is because the causal mechanism is different. Therefore, there may be contexts where timing of season has minimal effect on risk assessment, but large effects on risk tolerance, or vice versa.

4.4.2 From StARRT to Decision-Tree Analysis

The StARRT framework is not new. It is simply applying a Decision Theoretic approach to the context of RTS. More complicated versions are possible and would lead to decision-tree analysis. In a full decision-tree analysis, we evaluate the causal effects of choosing one action (allowing RTS) over another (not allowing RTS). If we consider reinjury and mental health as outcomes, the following four scenarios are possible: injured and good mental health, injured and poor mental health, uninjured and good mental health, and uninjured and poor mental health. One might consider that uninjured and poor mental health is unlikely since the athlete is doing their activity and should be in a good mental state. However, within the biopsychosocial model, if an athlete is not psychologically ready, there might be high anxiety for an extended period of time, and this could have effects outside of sport.

In a full decision-tree analysis, one would attach probabilities to each of the four scenarios. To the extent possible, the probabilities would be based on actual risk scores developed from surveillance or intervention studies (similar to Framingham Risk Score for cardiovascular disease [21]). At the end of the process, one still needs to make a value judgement. If the risks are all the same, the value judgement is simply about which state is preferable. For example, is it better to be uninjured with a poor mental state or injured with a healthy mental state? If the risks are different, the question might be whether one would prefer a 20% risk of being uninjured with a poor mental state compared to a 30% risk of being injured with a healthy mental state. As these are value judgements, there are no algorithms or statistical analysis that can provide the best answer for an individual athlete. Although computer programs can easily provide overall probabilities of each outcome, the calculation is based on several assumptions that may or may not be true. In the end, the optimal choice will depend on many factors, including the personal values of the decision-maker.

4.5 The Athlete's Best Interests?

In this chapter, I have referred to "best interests of the athlete" several times. How do we define "best interests"? If athlete's best interest is our objective, we need to define the term before we can decide on a process to achieve it. However, as different people have different personal and societal values, how can this be done? For this discussion, I loosely define the best interests to include some combination of the athletes' needs, desires, and interests. Each of these is a distinct construct even if there is overlap between them.

Every independent person has the authority to make decisions about their own risks for health unless otherwise restricted by law (e.g. helmets while driving motorcycles in many countries) or the person is deemed not capable of providing consent through diminished mental capacity. However, in sport and other work-related injuries, many jurisdictions require that a medical doctor approve the return to activity. This loss of autonomy for healthy athletes can be challenging. In this section, we discuss different approaches on deciding who should have the authority to make the decision, when, and why. In the next section, we discuss some advantages and disadvantages of giving each of the following the power to decide: the athlete (or designated representative such as parent or power of attorney), any one of the clinicians (e.g. medical doctor, physiotherapist, athletic trainer, chiropractor, nurse, nutritionist), coach, management (e.g. sport association, team employer), the athlete's family, an agent, or some multidisciplinary team made up of a combination of the above stakeholders.

The interactions between the athlete, family, friends, agents, coaches, clinicians, and institutional or corporate managers are often complex and confusing. Although there have been discussions of power relationships in medical sociology [22], this has not occurred within the context of RTS decisions. Even though shared decision-making promotes "negotiation" approaches to treatment [23], power relationships remain as the ultimate decision-making power usually resides with the clinician. When athletes avoid interaction with clinicians [23], they retain power over the decision-making process by default except where the clinician's approval is expressly required.

The StARRT framework first requires an assessment of risk. Are clinicians better at assessing risk than others? Are some clinicians (e.g. medical doctors) better than others at assessing risk (e.g. physiotherapists)? We asked members of different Canadian sport medicine professional groups to rank which professional group members might be best to answer such questions [20]. In general, most participants ranked medical doctors as the most capable to assess the health of the tissue, even though there are no studies evaluating this capacity. With respect to risk of reinjury, short-term and long-term consequences, medical doctors believed medical doctors were best, physiotherapists believed physiotherapists were best, and chiropractors believed chiropractors were best. Of the non-clinician groups, official sport association members generally believed medical doctors were best, athletes believed physiotherapists were often equal or better than medical doctors, and coaches believed physiotherapists and medical doctors were generally equal but medical doctors were better at assessing long-term consequences. When the same respondents were asked which group had the greatest capacity to assess the importance of risk tolerance modifiers, the athletes and coaches were generally considered the best.

In making a RTS decision, one would naturally want to obtain the most valid information. The results above suggest that an informed decision requires information from several sources. Risk tolerance is a value judgement. Further, there are many different outcomes that need to be evaluated and synthesized if the decision-maker is to act in the best interests of the athlete. How many medical doctors have spent enough time with an athlete to truly understand their wishes, dreams, or psychological stability? How can a coach evaluate potential suffering due to a possible future consequence of severe osteoarthritis? Two different medical doctors are likely to have different risk tolerances; which of these risk tolerances represents the best interests of the athlete? Is it really possible for clinicians to block out their own conflicts of interest with respect to association with a team? As much as one might try, there may be an unconscious or conscious bias to allow the athlete to RTS even though the risk assessment suggests a risk higher than the decision-maker's risk tolerance level in the absence of this fear. Is a coach any different?

4.6 Which Stakeholder Should Be the Decision-Maker?

Table 4.1 summarizes some major strengths and weaknesses of each of the stakeholders to make an ethical RTS decision. Sport medicine follows a Workers' Compensation model, where the underlying assumption is that a medical doctor's opinion is independent and therefore protects the worker from unreasonable pressure by the employer. However, team health professionals (e.g. medical doctors, physiotherapists, athletic trainers) are usually hired by the team and therefore have dual allegiances. Athletes may obtain recommendations for RTS from non-team clinicians, but the team health care professional usually retains the final decision-making power unless legal proceedings ensue.

When several health professionals are involved in caring for the same athlete, an already complex situation becomes more difficult and lines of communication and authority must be clearly defined [1]. According to one consensus document, the essential elements for RTS decisions are the safety of the injured athlete and other athletes, as well as compliance with any rules or regulations [1]. The role of social and economic factors with respect to overall health and well-

Table 4.1 Strengths and weaknesses when the decision-maker is a particular stakeholder

Stakeholder	Strengths	Weaknesses
Clinicians		
Medical doctor	Knowledge about injury risk and consequences of injury. More often not an employee of management so less probability of coercion	Less personal contact with individual athletes and may not understand them as well
Team therapist[a]	Knowledge about injury risk and consequences of injury. Generally know athletes better than medical doctors	Usually an employee of management and may have less perceived power than medical doctor. This might mean more likely subject to coercion
Other (e.g. nutritionist, psychologist)	Similar to medical doctors and usually knowledgeable about injury/illness risk and consequences of injury/illness within their field of expertise	Usually a paid consultant to management. If perceived power is less than a medical doctor, then more subject to coercion
Non-clinicians		
Athlete	Knowledge of the athlete's global needs is near complete (but not complete). By definition, provides the best source for information about athlete's needs and values	Only has personal experience about injuries incurred so knowledge base is limited. Difficulty assessing risk. During heightened emotion of competition, may not be able to properly weigh risks and benefits even if given information. For injuries affecting cognition (e.g. concussion), informed consent is not possible
Coach	Often aware of athletes' strengths, desires, and values. On occasion, will have a more complete view of athlete's benefits such as sport career potential	Limited experience to evaluate risk. During heightened emotion of competition, may be difficult to properly evaluate risks. Potential conflict if athlete may be important to win the game
Family, friends	Often strong knowledge of athlete's global needs, desires, and values	Least experience to evaluate risk. On occasion, could be motivated by own personal gains if athlete RTS
Management (sport association, team)	Often aware of career potential and the benefits (or lack thereof) that can occur with RTS	Objective to win may increase risk tolerance even though athlete would not benefit

[a]The term "team therapist" is used to refer to any one of the professions that has clinical training to evaluate and treat sport injuries and illnesses. In some cases, the term used to represent a valid clinical profession in one country represents a completely different (and invalid) profession in another country. Team therapists are often physiotherapists, athletic therapists, athletic trainers, chiropractors, and massage therapists

being within an RTS context has not been explicitly studied [24]. Without clear recommendations about which factors must be included in the RTS decision, clinicians must rely on their own value and belief systems, which often include issues other than safety [23].

To make an informed decision as required by law, an athlete's mental status must be sufficient to evaluate the short-term and long-term consequences of the decision. In injuries such as concussion, the ability to process information is clearly impaired. Even in a healthy athlete, is it possible to evaluate and process complex information during a competition when decisions have to be made very rapidly, and emotions are strong during the event? Unfortunately, our cognitive ability under these conditions has not yet been evaluated.

One might argue that outside of competition, the athlete should have the time available to become informed and to evaluate the different consequences with respect to all aspects of health. Yet our current framework treats in-competition and out-of-competition the same. For the athlete, how well can clinicians and others evaluate the following factors that have been linked to low self-esteem and depression [2]?

1. Injury may represent a form of body-betrayal and a source of self-resentment [25].
2. Psychological needs such as the desire to compete or "love of the game" [26].

3. Sociocultural influences and status amongst peers and fans may affect mental health and stability [2, 25].
4. Not playing when injured can lead to identity crises, feelings of guilt and shame, or experiences of alienation from the team [26–28].

At the same time, although some athletes would like to be more involved in RTS decisions themselves [26], others (1) indicate they have learned to trust medical doctors and trainers to make decisions for them [27] and believe it is important for medical personnel to prevent them from returning to sport prematurely [29] or (2) reported being pressured into returning to sport too early by the medical doctor, trainer, or coach [28].

Some coaches believe athletes can be caught in a "risk-pain-injury paradox" and that the coach should push athletes to maximize athletic performance without taking excessive risks [30]. This may include competing while injured. Coaches also see their role as managing unrealistic athlete expectations about progress following an injury and RTS [28].

It is clear that management's objective is to win, and there is a strong possibility of conflict of interest. That said, management may have important information and perspectives to offer with respect to career potential, and some management may have a longer-term view and want to maximize the longevity of the athlete.

Interactions with family, friends, agents, and institutional or corporate managers are often complex and confusing. These stakeholders are often accused of placing "non-health issues" above "health issues", but the definition of "health" is often defined very narrowly and may not represent the overall best interests of the athlete.

4.6.1 Protecting the Athlete with a Multidisciplinary Approach?

Assuming we agree on a definition of "best interests", the key to an ethical process is to minimize the risk of coercion and misrepresentation of information. Could a process that uses a multidisciplinary team approach to decision-making achieve this?

Potential conflicts of interest, both conscious and subconscious, exist for each stakeholder. Some individuals may be better at recognizing these than others. One advantage of a team approach is that each team member can help ensure that others' (and their own) potential conflicts of interest are made transparent and documented. The transparency may also provide decision-making team members with insight into issues that were only operating subconsciously. Finally, the team approach and documentation may temper inappropriate enthusiasm for an option that benefits the proponent of the decision as opposed to the well-being of the athlete.

A team approach is not without challenges. First, in-competition decisions must be made quickly and a team approach would not be feasible. Second, although conflicting values between team members are made transparent, they remain. By their nature, decisions about risk assessment and risk tolerance can elicit strong emotions. Therefore, there is a risk that a team approach may create interpersonal conflicts that would otherwise be avoided when there is one clear decision-maker. Third, a mechanism must be available to resolve conflicting opinions: either the athlete returns to a level of activity or does not return to the level of activity. Does each member have one vote, or do we weight members' votes to account for their different capacities and potential conflicts of interest? This theoretical perspective may provide a significant voice to aspects of athletes' well-being that may otherwise go ignored, but can such a method be operationalized?

The current model is effective and efficient when athletes agree with the RTS decision. However, when athletes disagree, they may sue to be able to play or sue when allowed to play and adverse events occur. In both cases, the current model has judges as the final decision-maker to determine athlete well-being. However, why should judges be considered the best to determine the best interests of an athlete? What training do they have to understand the biopsychosocial consequences of injury and RTS? Exploring solutions to the challenges mentioned above may result in a more stable and ethical model.

4.7 Summary

In this chapter, we explained how we should consider the RTS decisions within the broader context of caring for the athlete as a person. When caring for the athlete requires RTS decisions, the first two steps of the StARRT framework address risk assessment, and the third step focuses on factors that can modify the RTS decision-based risk tolerance. After considering all the factors, if the risk of the outcome is less than the risk tolerance, the decision should be to RTS. Otherwise, the decision should be no RTS.

The current decision-making process occurs within a social context that is affected by the values, beliefs, and attitudes of a single decision-maker. The steps are not always transparent and may lead to confusion and unnecessary conflict. Regardless of who is given the authority to make the final RTS decision, each of the stakeholders has information that might be helpful in understanding the best interests of the athlete, and each of the stakeholders is likely to have conscious or subconscious conflicts of interest. To borrow a thought from Winston Churchill, our current process seems to be the worst form of decision-making, "… except for all those other forms that have been tried from time to time" [31]. Hopefully we will continue to be creative and think of newer and better ideas that lead to more consistent decisions that favour athlete well-being and minimize conflict.

Acknowledgements

- Jay Mellette of the Vegas Golden Knights for developing the concept behind the FAIR model
- Lyn Charland for creating the acronyms StARRT (Strategic Assessment of Risk and Risk Tolerance) and FAIR (From Activity to Injury and Rehabilitation/Reintegration)

References

1. The team physician and return-to-play issues: a consensus statement. Med Sci Sports Exerc. 2002;34(7):1212–4.
2. Wiese-Bjornstal DM, Smith AM, Shaffer SM, et al. An integrated model of response to sport injury: psychological and sociological dynamics. J Appl Sport Psych. 1998;10:46–69.
3. Roderick M, editor. The world of professional football. London: Routledge; 2006.
4. Safai P. Negotiating with risk: exploring the role of the sports medicine clinician. In: Young K, editor. Sporting bodies, damaged selves: sociological studies of sports-related injury. Oxford: Elsevier; 2004. p. 269–86.
5. Safai P. Sports medicine, health, and the politics of risk. In: Andrews DL, Carrington B, editors. A companion to sport. Malden, MA: Wiley-Blackwell; 2013. p. 112–28.
6. Malcolm D. Medical uncertainty and clinician-athlete relations: the management of concussion injuries in rugby union. Sociol Sport J. 2009;26(2):191–210.
7. Shrier I. The strategic assessment of risk and risk tolerance (StARRT) framework for return to play decision making. Br J Sports Med. 2015;49:1311–5.
8. Creighton DW, Shrier I, Shultz R, et al. Return-to-play in sport: a decision-based model. Clin J Sport Med. 2010;20(5):379–85.
9. Shultz R, Bido J, Shrier I, et al. Team clinician variability in return-to-play decisions. Clin J Sport Med. 2013;23(6):456–61.
10. Shrier I, Matheson GO, Boudier-Riveret M, et al. Validating the 3-step return to play decision model. Scand J Med Sci Sports. 2015;25(2):e231–9.
11. Pincus T, Kent P, Bronfort G, et al. Twenty-five years with the biopsychosocial model of low Back pain – is it time to celebrate? A report from the twelfth international forum for primary care research on low Back pain. Spine. 2013;38(24):2118–23.
12. Ayers DC, Franklin PD, Ring DC. The role of emotional health in functional outcomes after orthopaedic surgery: extending the biopsychosocial model to orthopaedics. J Bone Joint Surg Am. 2013;95(21):e165.
13. Atkins E, Colville G, John M. A 'biopsychosocial' model for recovery: a grounded theory study of families' journeys after a paediatric intensive care admission. Intensive Crit Care Nurs. 2012;28(3):133–40.
14. Ardern CL, Glasgow P, Schneiders A, et al. 2016 consensus statement on return to sport from the first world congress in sports physical therapy, Bern. Br J Sports Med. 2016;50(14):853–64.
15. Ardern CL, Taylor NF, Feller JA, et al. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med. 2014;48(21):1543–52.

16. Reyna VF, Rivers SE. Current theories of risk and rational decision making. Dev Rev. 2008;28:1–11.
17. Ashby D, Smith AF. Evidence-based medicine as Bayesian decision-making. Stat Med. 2000;19:3291–305.
18. Shakespeare TP, Gebski VJ, Veness MJ, et al. Improving interpretation of clinical studies by use of confidence levels, clinical significance curves, and risk-benefit contours. Lancet. 2001;357(9265):1349–53.
19. Shrier I. Muscle dysfunction versus wear-and-tear as a cause of osteoarthritis: an epidemiological update. Br J Sports Med. 2004;38:526–35.
20. Shrier I, Safai P, Charland L. Return-to-play following injury: whose decision should it be? Br J Sports Med. 2014;48:394–401.
21. National Heart, Lung, and Blood Institute. Risk assessment tool for estimating your 10-year risk of having a heart attack. 2013. http://cvdrisk.nhlbi.nih.gov/. Last accessed: 12 Dec 2014.
22. Gabe J, Bury M, Elston MA, editors. Key concepts in medical sociology. Thousand Oaks, CA: Sage Publications; 2004.
23. Safai P. Healing the body in the "culture of risk": examining the negotiation of treatment between sport medicine clinicians and injured athletes in Canadian Intercollegiate Sport. Sociol Sport J. 2003;20:127–46.
24. McFarland EG. Return to play. Clin Sports Med. 2004;23:xv–xxiii.
25. Young K, White P, McTeer W. Body talk: male athletes reflect on sport, injury, and pain. Sociol Sport J. 1994;11:175–94.
26. Podlog L, Eklund RC. A longitudinal investigation of competitive athletes' return to sport following serious injury. J Appl Sport Psych. 2006;18(1):44–68.
27. Nixon HL. Accepting the risks of pain and injury in sport: mediated cultural influences of playing hurt. Sociol Sport J. 1993;10:183–96.
28. Podlog L, Eklund RC. Professional coaches' perspectives on the return to sport following serious injury. J Appl Sport Psych. 2007;19(2):207–25.
29. Podlog L, Eklund RC. The psychosocial aspects of a return to sport following serious injury: a review of the literature from a self-determination perspective. Psychol Sport Exerc. 2007;8:535–66.
30. Nixon HL. Coaches' views of risk, pain, and injury in sport, with special reference to gender differences. Sociol Sport J. 1994;11:79–87.
31. Churchill W. Speech in the house of commons. The official report, house of commons, 5th series, vol. 444. 1947. p. 206–7.

5 Role of the Team Physician, Orthopedic Surgeon, and Rehabilitation Specialists

Eileen A. Crawford and Edward M. Wojtys

5.1 Introduction

When athletes suffer a season-ending knee injury such as an anterior cruciate ligament (ACL) rupture, their thoughts of return to sport (RTS) begin almost immediately. The goal of ACL reconstruction surgery is indeed to restore the knee stability that is necessary for jumping, cutting, and pivoting sports and certain activities of daily living. Yet, returning to sports is far from guaranteed following ACL reconstruction. While approximately 80% of these patients will be able to return to some level of sports participation, only about two-third return to their previous level of sport and one-half to a competitive level of sport [1, 2]. Younger patients may have more optimistic odds. A systematic review and meta-analysis on RTS following ACL reconstruction in patients aged 6–19 years old reported that 92% returned to any level of sports, 79% returned to previous levels, and 81% returned to competitive level of sport [3]. For those who do RTS following ACL reconstruction, the risks of graft rupture and contralateral ACL rupture are not insignificant.

There are many reasons for not achieving a return to the previous level of sport, including poor surgical outcome, inadequate rehabilitation, and psychological barriers. Some patients simply elect to transition to other interests and priorities [1, 3]. For athletes who desire a return to the level of sport they previously enjoyed, there are numerous opportunities for the treating medical professionals to intervene and improve the likelihood of achieving this goal. The expertise needed to facilitate this goal is varied and best achieved with a concerted effort from a knowledgeable sports medicine team consisting of the orthopedic surgeon, team physician, and rehabilitation specialists (physical therapists and athletic trainers). The purpose of this chapter is to identify these opportunities and explain the need for intervention on the part of the sports medicine team, with focus on the preoperative, early postoperative, late postoperative, and RTS phases of rehabilitation.

5.2 Preoperative Phase

Even before surgery is scheduled, there are steps to take toward a successful RTS. Perhaps the most critical is setting reasonable expectations for the athlete. This includes expectations regarding time away from sports, commitment to rehabilitation, restrictions during the recovery phases, goals to be met prior to RTS, risks of reinjury and

E. A. Crawford (✉) · E. M. Wojtys
Division of Sports Medicine and Shoulder Surgery, Department of Orthopaedic Surgery, University of Michigan, Ann Arbor, MI, USA

Medsport, Ann Arbor, MI, USA
e-mail: ceileen@med.umich.edu

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_5

contralateral injury, and the possibility of not returning to sports at the same level. The orthopedic surgeon typically sets these expectations and is charged with communicating them to the physical therapists, athletic trainers, and any other team physicians involved in the athlete's care. Because rehabilitation timelines and postoperative restrictions vary from surgeon to surgeon, documented protocols are important to ensure that the athlete, coaches, and sports medicine team members are all aligned in their expectations. They also allow the expectations to be reinforced by each of the team members, making it more likely for the message to come through to the athlete as intended. This list of expectations includes an enormous amount of information to convey in a single orthopedic clinic encounter, and the amount of verbal information retained by a patient after receiving a diagnosis of ACL rupture is undoubtedly low.

After hearing the diagnosis and recommendation for surgery, the primary question on the athlete's mind is usually, "How soon can I get back to sports?". They expect a concrete and numeric answer, which they use to calculate how much and which parts of their athletic careers they will miss. Six months from surgery is a common response, with 9–12 months often used for preadolescent patients. Being goal-setters and high achievers, athletes will commonly latch on to a shorter timeframe, confident that they will be ready by then, if not sooner. In fact, the percentage of patients who are able to pass a series of post-ACL RTS tests at 6 months is usually 0–7% [4]. The more prudent response from the clinician involves giving a minimum time away from sports, while emphasizing that specific goals must be reached before RTS is permitted, and that many high-level athletes need more than 6 months to achieve these goals. Each extra month that RTS is delayed affords a 51% reduction in the reinjury rate up to 9 months [5], so waiting can be well worth it. Explaining that graft maturation and restoration of normal neuromuscular, proprioceptive, and biomechanical patterns following ACL reconstruction can take up to 2 years [6, 7] puts the significance of the injury and required recovery into perspective. The athletic trainer (or parent/guardian when no athletic trainer is involved) should convey the same message to the coaching staff so that the athlete does not feel pressured by coaches or teammates to RTS before being released by the surgeon.

The investment in rehabilitation following ACL reconstruction is easily underestimated. Patients should be counseled from the outset that participating in physical therapy multiple times a week as well as daily exercise for several months is a crucial part of the recovery process. The resources of time, transportation, and finances needed to engage in ACL rehabilitation are substantial for the patient and family members. Accommodations can sometimes be made to ease the burden, such as stacking physical therapy visits at certain phases of recovery and enrolling in transitional physical therapy programs that allow the use of equipment without direct interaction of the physical therapist for a nominal fee. Using accommodations appropriately requires planning based on reasonable expectations and communication between the patient, rehabilitation specialists, and surgeon.

Concomitant chondral, meniscal, and ligamentous injuries often warrant modifications to the rehabilitation protocol for ACL reconstruction, and these should also be clearly communicated before surgery to optimize compliance. For example, weight-bearing is typically delayed when a chondral repair or restoration procedure is combined with the ACL reconstruction. In contrast, small untreated chondral lesions do not necessitate a change in the protocol [8]. Limiting deep knee flexion following meniscal repair surgery is usually accomplished with a lockable hinged knee brace, and physical therapy exercises done out of the brace should adhere to the same limitations. For combined ACL and collateral ligament reconstructions, an extended course of postoperative bracing is commonly used to limit strain on the graft, and athletes should expect a longer time before RTS. Excessive scar formation should be expected following these combined injuries, so particular attention to regaining range of motion (ROM) in the early postoperative weeks is extremely important [9].

Finally, setting realistic expectations regarding the rates of reinjury and RTS is an essential component of the preoperative discussion. The rate of second ACL injury, whether ipsilateral graft failure or contralateral ACL rupture, ranges from 5% to 25% [2, 4, 10–12]. Younger age (<25), female gender, and return to cutting and pivoting sports have all been associated with increased risk of second ACL injury [2, 4, 10, 11]. The highest risk of reinjury occurs within the first 7 months following RTS [2]. A second ACL injury is devastating to the athlete who missed so many months of participation and worked so hard in rehabilitation only to circle back to the beginning. Although awareness of this possible outcome does not ease the disappointment, it does allow the athlete to make educated choices regarding his or her approach to RTS. Knowing that one-half to one-third of patients will not return to their previous level of sport [1, 4, 13] may also impact the short-term and long-term goals of the athlete. Among professional athletes, the ability to return to the preinjury level of play varies by sport, with basketball and soccer players more likely to experience a decrease in performance while hockey players, skiers, and snowboarders remain relatively consistent [4, 14–17]. A meniscectomy performed at the time of ACL reconstruction can shorten the expected career length for professional football players [18].

When first faced with an ACL injury, the athlete should revisit his or her goals and priorities. Multiple factors influence the progression of rehabilitation and RTS, including age, stage of the athletic career, time of the athletic season, level of play, contract commitments, and family commitments [10]. Orthopedic surgeons, team physicians, physical therapists, and athletic trainers all have a role to provide the athlete with feedback and evidence-based guidance to assist in modifying goals as needed. Middle school, high school, and collegiate athletes tend to think only of the immediate future, and they should be informed of the impact their injuries and choices have on the function of their knees over the coming decades.

Preoperative rehabilitation, or "prehab," starts as soon as the diagnosis and surgical management are established. Prehab is key preparation for a successful recovery and should not be glossed over in favor of a sooner surgery date as that can have a contradictory effect. The intent of prehab is to reduce swelling, restore full knee ROM, normalize gait, and minimize muscle atrophy and postoperative neuromuscular deficits [7, 9, 10]—essentially work the knee back to its preinjury appearance and function as closely as possible. This can typically be accomplished within 3–4 weeks from the injury [9, 10]. Failure to achieve adequate knee ROM prior to surgery puts a patient at risk for postoperative stiffness since preoperative and postoperative knee ROM are strongly correlated [10]. Patients who undergo extensive preoperative physical therapy have superior functional outcomes and higher rates of return to preinjury level of activity [19].

A secondary benefit of prehab is that it increases the number of preoperative interactions between the athlete and the sports medicine team. The physical therapists working with the athlete should take advantage of this time to reinforce expectations, take stock of the athlete's support system, and evaluate the athlete's motivation, compliance, and psychological outlook on the injury. Particularly in young patients who rely on others for transportation, having an adequate support system can make the difference in achieving a successful outcome. Early identification of issues with motivation, compliance, and psychological outlook allows time to troubleshoot before they become more detrimental. The orthopedic surgeon or team physician may schedule a second preoperative visit to ensure prehab goals have been met, and this also provides another opportunity to answer questions and assess the patient's understanding of the postoperative course.

Another important discussion between the orthopedic surgeon and the athlete involves graft selection for ACL reconstruction. While each of the different graft options has advantages and disadvantages, the biology of healing favors certain grafts when a more aggressive rehabilitation is desired. For allograft tissue, the slower ligamentization process compared to autograft negates the benefit of avoiding donor site morbidity. ACL reconstruction with allograft requires a longer period of restriction from jumping, cutting, and pivoting activities and is associated with a higher failure rate in young, active patients [9, 20–22]. The ligamentization process and graft-to-tunnel healing occur more rapidly in patellar tendon autograft compared to hamstring tendon autograft, which may justify faster progression through the rehabilitation stages [7, 9, 10]. The loss of dynamic medial knee stabilizers with hamstring harvest also makes it a less optimal choice for athletes planning to return to jumping, cutting, and pivoting sports. Athletes with significant hyperextension, which is common in gymnasts and many young athletes, tend to stretch out hamstring autograft over time [10]. In contrast, wrestlers are generally less tolerant of kneeling pain, which is more common following patellar tendon harvest. Hamstring or quadriceps tendon autograft may be better options for athletes in whom kneeling pain is a major concern. However, the discomfort is usually short-lived with good surgical technique. There are multiple considerations and trade-offs in graft selection that impact ultimate RTS. Even the savvy patient will benefit from the guidance of the orthopedic surgeon regarding graft options.

5.3 Early Postoperative Phase

The crux of the early postoperative phase lies in striking the right balance between forward progress and restful healing. Moving too slowly risks muscle atrophy and stiffness that is difficult to reverse and can impact RTS. Moving too quickly excessively strains the graft before ligamentization and tunnel healing are complete, risking graft failure. The athlete relies on the orthopedic surgeon and physical therapists to provide guidance on the pace of rehabilitation. The appropriate pace is not intuitive to the patient, who wants to rest while the knee hurts and get back to a regular life once the knee begins to feel normal again.

The first 2 weeks following ACL reconstruction surgery are a critical window for prevention of avoidable complications. At the first postoperative visit, ideally less than a week from the date of surgery, the orthopedic surgeon should personally examine the patient's knee. Patients often come to the first visit resting the knee in mild flexion despite verbal and written warnings against doing so. Failure to recognize and correct this at the first postoperative visit can lead to a permanent flexion contracture. As little as 5° of extension loss can result in long-term patellofemoral pain, quadriceps weakness, and gait abnormalities [2]. These deficits can translate into delayed or incomplete RTS and eventual degenerative changes in the knee [10]. Knee aspiration may be necessary for a large effusion to allow full knee extension and relieve the quadriceps inhibition caused by the effusion. Smaller knee effusions may respond to aggressive cryotherapy and compression, which can be reinforced at the first visit. Vastus medialis inhibition occurs with only 20–30 mL of fluid in the knee, and vastus lateralis and rectus femoris inhibition occurs with 50–60 mL of fluid [23]. After addressing the effusion, the patient should be instructed in stretching exercises for regaining full active and passive knee extension (Fig. 5.1). A physical therapist or athletic trainer who is present for this first postoperative visit is a huge asset, as they can provide hands-on instruction for the patient in a daily home exercise program. This is particularly helpful for patients who are not scheduled to start physical therapy immediately after the visit. The goal is to obtain full active and passive knee extension, equal to the contralateral side, within 2 weeks of surgery [2, 24]. Additional physical

Fig. 5.1 This passive knee stretching exercise is performed to regain full extension in the early postoperative phase. A bolster is placed under the ankle and a weight is placed over the distal thigh to create a gradual stretch over the course of 10–15 min (adapted from Wilk and Arrigo [9]. Reprinted by permission of Elsevier via Rightslink)

therapy appointments or postoperative clinical visits may be needed to ensure this goal is met.

Regaining full knee flexion, while still an important part of early rehabilitation, occurs on an intentionally slower timeline. The goal time to achieving full knee flexion is approximately 6–8 weeks for an isolated ACL reconstruction [2]. Pushing knee flexion too quickly can exacerbate pain and swelling, which is counteractive to future progress [9]. Deep knee flexion may also be undesirable for concomitant procedures such as meniscal repair. Continuous passive motion devices are not routinely used following ACL reconstruction due to the lack of substantial supporting evidence [2, 8]. Patients should be made aware of the supremacy of extension over flexion motion in the early postoperative weeks so that they focus their stretching exercises in physical therapy and their home exercise program.

Patellar mobilization exercises are started immediately as a means of minimizing anterior scar tissue formation so that knee flexion returns with less difficulty over the ensuing weeks. Restoring patellar mobility is also essential to recovery of quadriceps function and avoidance of excessive forces in the patellofemoral compartment [9]. Once instructed in patellar mobilization exercises by a rehabilitation specialist, the patient can perform them independently on a daily basis.

Another common complication to combat in the early postoperative phase is quadriceps weakness. This starts with quadriceps activation exercises with the knee in full extension, which can be performed before any active ROM has returned. Neuromuscular electrical stimulation (NMES) units may also expedite the recovery of quadriceps strength [2]. NMES can be prescribed for use in the early weeks following surgery, both at physical therapy and with a home unit. A systematic review demonstrated greater isometric quadriceps torque, peak quadriceps torque, and isokinetic knee extension strength with use of NMES [25]. Patients work toward performing a straight leg raise against gravity without an extension lag. These early interventions are necessary for restoring normal, unassisted ambulation. While postoperative bracing has not shown any benefits on ultimate outcome following ACL reconstruction, the use of a knee immobilizer or hinged knee brace locked in extension allows progression of weight-bearing while patients are still in the early stages of quadriceps strengthening [24].

The rate at which goals are achieved in this early postoperative phase varies from patient to patient and is not always predictable from preoperative interactions with the patient. An important role of the rehabilitation specialists is to identify and manage patients who are progressing too quickly or too slowly. These concerns should be communicated to the orthopedic surgeon, who may then choose to modify the rehabilitation protocol or meet with the patient to reinforce expectations. The frequency of physical therapy visits during this phase should be agreed upon by the physical therapist and orthopedic surgeon based on the individual patient's rate of progression. Patients who are slow to regain ROM and quadriceps activation because of pain, swelling, fear, or other factors will benefit from several sessions per week. Due to insurance limitations on the total number of covered sessions, stacking visits in the early postoperative phase may necessitate less frequent visits later in the rehabilitation process [2]. This adjustment will be worthwhile to the slowly progressing patient because the overall pace of recovery is typically set in the early weeks. In contrast, the patient who has minimal pain and swelling and quickly regains ROM and quadriceps activation may do well with once weekly physical therapy sessions. This preserves sessions for later rehabilitation phases when more attention to residual neuromuscular deficits and proper body mechanics may improve the chances of a timely RTS [2]. However, not all patients who are progressing quickly will be appropriate for this adjustment. Patients who have minimal pain but do not understand the need for healing on a cellular level are at risk for pushing past restrictions if given too much independence with their rehabilitation. ACL grafts are weakest between 4 and 12 weeks postoperatively, a window when young patients in particular begin feeling more normal and are tempted to return to their active lives [24].

As in the preoperative phase, communication between the orthopedic surgeon, rehabilitation specialists, team physician, and athlete is of utmost importance in the early postoperative phase. Athletes are usually highly motivated in their rehabilitation, but physical therapy of this intensity is an unfamiliar experience for most. They need to hear consistent instructions from the entire sports medicine team, who should explain the rationale for restrictions in basic terms to improve compliance. All parties should be made aware of concomitant procedures performed with the ACL reconstruction, such as bony realignment, meniscal repair, and articular cartilage restoration or repair, and how these procedures impact the rehabilitation protocol [2]. At the authors' institution, postoperative visits are conducted adjacent to the physical therapy gym. For patients who perform their physical therapy on-site, this setup allows the treating physical therapist to attend the visit, provide valued insight to the surgeon, and participate in management strategies. Communication is immediate and confirmed, and the athlete receives a unified message. This resource is clearly not available in all orthopedic practices, and not practical for patients who live far from that location. In these cases, establishing a timely line of communication between the local rehabilitation specialists and the orthopedic team allows prompt identification and management of patients who are progressing too slowly or too quickly.

5.4 Late Postoperative Phase

The goals of the early postoperative phase—a pain-free, uninflamed knee with full ROM, good quadriceps activation, and a normal gait—are followed by a focus on neuromuscular retraining, visual-motor training, and increasing work load. An ACL rupture disrupts not only the collagen fibers but also the neural circuits between the knee and the brain that drive motor patterns [4, 26–28]. This proprioceptive capacity is not typically restored within the standard RTS timeframe. Therefore, proper movement patterns must be intentionally retrained through repetition and feedback from an experienced rehabilitation team. Continued training is often necessary long after the athlete has RTS, and the need for endurance building is crucial to avoid reinjury [4]. Developing the neuromuscular control needed to return to jumping, cutting, and pivoting sports safely is a complex process that requires "adequate strength and mobility, kinesthetic awareness, efficient joint mechanics, and a sufficiently adaptive motor control system" [6]. It is not the type of rehabilitation that can be accomplished solely with a home exercise program, so patients should not be discharged from physical therapy before this phase.

The foundation of neuromuscular retraining is built with progressive strength training and identification of residual strength deficits. Closed kinetic chain exercises reveal strength deficits in the operative lower extremity, while open kinetic chain exercises isolate the specific muscles or muscle groups that harbor the deficit [29]. The quadriceps and the hamstrings tend to get the most attention in ACL rehabilitation programs, but muscular weakness and atrophy of other muscle groups frequently occurs during the period of protected weight-bearing and activity restriction. Deficits in core and hip abductor and external rotator strength can result in abnormal landing patterns that lead to a second ACL injury [11]. Therefore, these muscle groups should also be targeted and tested by the physical therapist prior to advancement to the final stage of rehabilitation.

Comparison to the contralateral extremity is commonly used as a gauge for progression to running and sport-specific training. Patients who achieve quadriceps and hamstring strength of at least 75–80% of contralateral lower extremity may be permitted to begin running and light plyometrics, whereas 85–90% is a standard threshold for sport-specific training [2]. Hop tests may also be utilized with side-to-side comparison to assess for progression to sport-specific rehabilitation activities. Side-to-side comparisons carry the caveat that strength deficits may also be present in the uninjured extremity, which might have been a contributing factor to the original injury. Unilateral ratios (e.g., hamstring to quadriceps) and knowledge of muscular activity in sport-specific motions and positions provide important supporting data for decisions on progression to the later stages of rehabilitation [24, 29]. Strength deficits are most notable during the first 6 months following surgery, but will persist to a lesser degree for 2 years or more [11]. The importance of continued efforts on reducing such deficits even after RTS should be emphasized to the athlete throughout the course of physical therapy.

Permission to begin a jogging or running program is a major milestone in ACL rehabilitation. As described above, the athlete should have achieved the set goals for pain, swelling, ROM, gait pattern, and strength to reach this milestone. In practice, however, a large proportion of patients are advanced to running purely based on the time from surgery. Rambaud et al. [30] published a scoping review of 201 studies to determine what criteria were used to decide when patients were permitted to begin running following ACL reconstruction. The median time to running was 12 weeks, and only 18% of examined studies reported using criteria other than time from surgery to determine when patients would be released to running [30]. Physical therapy protocols usually list ranges of postoperative weeks along with the different phases of rehabilitation. While this practice is intended as a guide for where the patient is expected to be in the recovery process and to set certain minimum parameters to protect the graft, providers who are inexperienced in ACL rehabilitation may rely too heavily on these dates to cue progression. Protocols should be written with clearly stated criteria for progression to subsequent phases. For example, Rambaud et al. proposed necessary criteria to begin running as: pain score less than 2 on visual analog scale, full knee extension, at least 95% of contralateral knee flexion, and minimal to no effusion [30]. Strength thresholds and functional tests for balance and dynamic loading are also appropriate to add to this list. If date ranges are included on the protocol, it should be clearly stated that patients should not be progressed without meeting the listed criteria regardless of where they are chronologically in the protocol. Conversely, patients who have met the criteria well ahead of schedule should not be advanced beyond the listed minimum time from surgery to allow for adequate graft incorporation [24].

The sport-specific training phase follows the progressive running program, again with specific criteria to be met before proceeding. This phase is not a release back to regular training with a team or coach, but rather a stage for practicing the complex movements required for sport in the controlled and non-competitive setting of physical therapy and/or athletic training. Strength and neuromuscular control are expected to be approaching normal by this stage, but require frequent feedback and fine-tuning. A systematic and gradual increase in workload is key to maintaining neuromuscular control and proper joint mechanics as fatigue develops [4]. The pressure for return to sport escalates around this time, as athletes, coaches, and family members see the end in sight. Orthopedic surgeons and team physicians are charged with standing firm to their data-based assessment of an athlete's readiness in face of this pressure. The use of formalized functional sports assessments, discussed in the next section provides objective support to the physician's stance on RTS.

5.5 RTS Phase

RTS is a phase of ACL rehabilitation, not a discrete time point, and should be presented to the athlete as such. One reason for this is that the functional sports assessment often reveals subtle deficits that need to be corrected and retested prior to a full release to competitive sports. Other factors such as psychological readiness and time in the athletic season may also warrant a more gradual RTS. Athletes should also be counseled by the orthopedic surgeon that since there is no biological threshold when the ACL graft transitions from "at risk" to "not at risk," reinjury prevention will be a long-term process that extends well past their RTS participation. Attention to neuromuscular control and other modifiable risk factors will limit the risk of reinjury but never fully eliminate it [10, 29].

While the orthopedic surgeon or team physician ultimately makes the decision to medically release the athlete back to sports training, the decision should be based on input from the athlete, physical therapist, and athletic trainer. It is important to recognize that being medically cleared to play does not necessarily mean ready to compete. These other professionals may have concerns or questions about RTS that do not surface during a postoperative visit with the orthopedic surgeon. While clinicians can determine readiness to train and practice, coaches will need to know when an athlete can compete. Wilk and Arrigo [9] proposed a three-stage RTS, with the first level involving sport-specific training, the second level allowing practice with other athletes, and the third level introducing game competition. The benefit of separating practice from game competition is that the athlete has more opportunity to self-regulate and reacclimate to playing with other athletes.

In 2011, Barber-Westin and Noyes [31] published a systematic review examining RTS criteria in the literature. Similar to the return to running criteria, time from surgery was the most commonly cited criterion for RTS (32%), with subjective and objective criteria cited only 15% and 13% of the time, respectively [31]. The past several years have seen a response to this concerning data, with the formalization of RTS testing using objective functional sports assessments at many institutions. Less attention has been given to the subjective, psychological issues surrounding RTS, though standardized assessment tools do exist.

The functional sports assessment (also referred to as functional movement assessment, functional testing algorithm, etc.) is a comprehensive series of tests that provides objective, qualitative, and quantitative data on the patient's risk of ACL reinjury and, by extension, readiness for a safe RTS [29]. Its content varies from one institution to another, but typically includes a combination of ROM and flexibility testing, strength testing, gait analysis, functional testing, and patient-reported outcomes. Ligament stability testing with an arthrometer, video analysis, and psychological outcome scores may also be included [29]. Results are provided in terms of overall risk of reinjury, acknowledging that zero risk is unachievable. The scores on each section of the test highlight the residual deficits that contribute to the overall risk assessment. It is critical for the physical therapist and/or orthopedic surgeon to review the results of the test in detail with the patient to communicate the areas for improvement, even for those deemed ready to begin sports participation. Shorter and less intense versions of the functional sports assessment may be developed for patients who do not intend to return to a competitive level of play or sports that require jumping, cutting, and pivoting [29].

The functional sports assessment is typically administered at least 5–6 months after surgery, and following completion of running and agility programs. Relatively simple tests can be performed in clinic to see if the athlete is even ready to undergo a functional sports assessment. These include 10 repetitions of a one-legged squat to evaluate for dynamic valgus and core stability, or a video drop-jump test to evaluate landing control with transition into a jump [11]. Poor performance on these tests indicates that more strengthening and neuromuscular control will be needed to pass the functional sports assessment, so time and resources need not be wasted at that point. If the athlete does seem appropriate for a functional sports assessment, the testing protocol can be developed based on available resources. Davies et al. [29] described the lower extremity functional test (LEFT), which is the final stage in their functional sports assessment, following physical examination, strength testing, ligament stability testing, and functional hop testing. The LEFT test incorporates eight different agility drills, all completed in under 3 min in a diamond-shaped area that is approximately 30 feet by 10 feet in area. The drills test the patient's responses to acceleration and deceleration, athletic maneuvers, and fatigue [29, 32]. The Hospital for Special Surgery Quality of Movement Assessment uses frontal and sagittal plane video and live analysis of 10 tasks, assessing the quality of movement with regard to strategy, depth, control, limb symmetry, and alignment. When testing was performed between 5 and 7 months postoperatively, 60% of patients demonstrated risky movement patterns in more than half of the tasks [4]. The application of functional sports assessments has indeed revealed that the expectation of RTS 6 months following ACL reconstruction surgery is not realistic for many patients. Preparing the athlete for this possibility is an important role of the orthopedic surgeon, team physician, and rehabilitation specialists in an effort to ease the ensuing disappointment, discouragement, and distrust of the treatment team that can accompany a poor test result.

The functional sports assessment used at the authors' institution is a standardized and comprehensive evaluation performed by the Sports Medicine Program clinicians specifically trained to administer the test. The quantitative portion compares the operative and nonoperative lower extremities in terms of strength, balance, jumping, frontal and sagittal plane hops, single leg squats, and agility, and measures core strength. The qualitative portion assigns scores based on power, control, knee flexion, varus/valgus motion, shock absorption, trunk stability, and hip/pelvic strategy (Fig. 5.2). Finally, a patient-reported confidence score is obtained from the ACL-Return to Sport after Injury (ACL-RSI) test (Fig. 5.3). Due to the time it takes to complete the test, it is scheduled as a separate visit and completed at the authors' institution regardless of where the patient completed postoperative rehabilitation. Patients are stratified as high, medium, or low risk for return to planting, cutting, pivoting, and impactful sports. The results of the test are reviewed with the patient at the end of the visit, and the orthopedic surgeon uses the test results to determine readiness for sports participation. Patients who have concerning deficits are prescribed additional rehabilitation and retested at a later date.

The patient-reported confidence score is a critical component of the functional sports assessment, reflecting the patient's trust that the reconstructed knee will function properly when sports are resumed. The fear of reinjury is one of the top reasons for failure to RTS and does not always align with the quantitative and qualitative results of testing [10, 33, 34]. Fear of reinjury is specific to the injury event itself, rather than the consequences of reinjury such as additional surgery, rehabilitation, and time away from sports. It manifests both psychologically and physiologically, with distrust of the knee, distraction, and abnormal muscular recruitment patterns that can

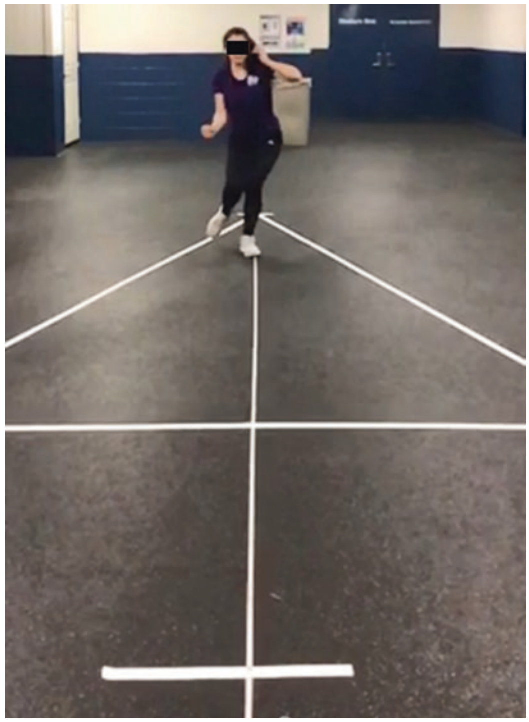


Fig. 5.2 This patient landing on the operative leg during a single-leg hop test demonstrates valgus collapse and poor balance and core stability, signs that she is not ready to return to sport

actually contribute to reinjury [34]. Mood disturbances, depression, anger, and decreased self-esteem are common in injured athletes, and can persist for several months following the injury [35]. There is some evidence to suggest that athletes with ACL injuries suffer greater and more enduring depression than those with concussions [36]. These emotions are strongest immediately following the injury, weakening over the course of rehabilitation only to reintensify as RTS approaches [34]. Affected athletes can be taught coping strategies, but it requires early identification of patients at risk for a disabling fear of reinjury. Orthopedic surgeons, physical therapists, and athletic trainers with an understanding of the fear of reinjury are best poised to identify these patients and initiate interventions.

The first step in managing at-risk patients involves asking patients about their emotions and their ability to cope with the injury and recovery [37]. This can be done verbally during

Anterior Cruciate Ligament-Return to Sport after Injury (ACL-RSI)

Instructions: Use the drop-down menu to indicate which best describes you in relation to the descriptors.

1. Are you confident that you can perform at your previous level of sports participation?

Not at all confident … Fully confident

0 10 20 30 40 50 60 70 80 90 100

2. Do you think you are likely to re-injure your knee by participating in your sport?

Extremely likely … Not likely at all

0 10 20 30 40 50 60 70 80 90 100

3. Are you nervous about playing your sport?

Extremely nervous … Not nervous at all

0 10 20 30 40 50 60 70 80 90 100

4. Are you confident that your knee will not give way by playing your sport?

Not at all confident … Fully confident

0 10 20 30 40 50 60 70 80 90 100

5. Are you confident that you could play your sport without concern for your knee?

Not at all confident … Fully confident

0 10 20 30 40 50 60 70 80 90 100

6. Do you find it frustrating to have to consider your knee with respect to your sport?

Extremely frustrating … Not frustrating at all

0 10 20 30 40 50 60 70 80 90 100

7. Are you fearful of re-injuring your knee by playing your sport?

Extremely fearful … No fear at all

0 10 20 30 40 50 60 70 80 90 100

8. Are you confident about your knee holding up under pressure?

Not at all confident … Fully confident

0 10 20 30 40 50 60 70 80 90 100

9. Are you afraid of accidentally injuring your knee by playing your sport?

Extremely afraid … Not afraid at all

0 10 20 30 40 50 60 70 80 90 100

10. Do thoughts of having to go through surgery and rehabilitation prevent you from playing your sport?

All of the time … None of the time

0 10 20 30 40 50 60 70 80 90 100

11. Are you confident about your ability to perform well at your sport?

Not at all confident … Fully confident

0 10 20 30 40 50 60 70 80 90 100

12. Do you feel relaxed about playing your sport?

Not at all relaxed … Fully relaxed

0 10 20 30 40 50 60 70 80 90 100

Fig. 5.3 The ACL-RSI survey is a tool developed by Webster et al. [38] that can be administered to the athlete to assess psychological readiness for return to sport

routine postoperative visits, or with the use of questionnaires administered at various points during rehabilitation [34, 37]. There are multiple questionnaires that are applicable for assessing psychological impact of ACL injuries. The ACL-Quality of Life (ACL-QoL) and ACL-RSI questionnaires are patient-reported outcome tools specific to ACL injuries. The Tampa Scale for Kinesiophobia (TSK) was developed to assess fear of movement and reinjury in patients with chronic pain but has been used for a variety of acute musculoskeletal problems including ACL injury, in its original and short versions (TSK-11) [34].

Referral to a sports psychologist is an appropriate next step for patients who are identified as having a notable fear of reinjury [37]. In general, it is beyond the scope of the orthopedic surgeon to characterize and treat problems with self-efficacy, self-esteem, and coping strategies, so management of these issues should be transferred to an expert. Counseling sessions may involve guided visualization, graded exposure, relaxation techniques, and positive self-talk [33, 34, 37]. A systematic review [33] of randomized controlled trials examining the use of psychological counseling following ACL reconstruction showed inconsistent benefits on postoperative function, quality of life, and fear of reinjury. However, counseling was provided to all study subjects, not just those demonstrating at-risk mental status [33]. The impact of psychological counseling on the fear of reinjury and RTS is yet undetermined, and future research is warranted on this topic.

5.6 Summary

Orthopedic surgeons, team physicians, and rehabilitation specialists have various roles and responsibilities to the ACL-injured athlete that begin before surgery and continue through the extended RTS phase. Throughout the course of rehabilitation, the key themes are (1) effective communication between the athlete and the entire sports medicine team, (2) preparation of the athlete for the demands and potential disappointments of ACL rehabilitation, (3) ongoing adjustments to the rehabilitation plan based on the variability of progression among individual athletes, and (4) attention to the athlete's mental state in addition to physical state. The science of RTS following ACL reconstruction is far from complete and will benefit from continued clinical and basic science research.

References

1. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med. 2014;48(21):1543–52.
2. Eckenrode BJ, Carey JL, Sennett BJ, Zgonis MH. Prevention and management of post-operative complications following ACL reconstruction. Curr Rev Musculoskelet Med. 2017;10(3):315–21.
3. Kay J, Memon M, Marx RG, Peterson D, Simunovic N, Ayeni OR. Over 90% of children and adolescents return to sport after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Knee Surg Sports Traumatol Arthrosc. 2018;26(4):1019–36.
4. de Mille P, Osmak J. Performance: bridging the gap after ACL surgery. Curr Rev Musculoskelet Med. 2017;10(3):297–306.
5. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med. 2016;50(13):804–8.
6. Di Stasi S, Myer GD, Hewett TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. J Orthop Sports Phys Ther. 2013;43(11):777–92, A1–11.
7. Sepulveda F, Sanchez L, Amy E, Micheo W. Anterior cruciate ligament injury: return to play, function and long-term considerations. Curr Sports Med Rep. 2017;16(3):172–8.
8. Thrush C, Porter TJ, Devitt BM. No evidence for the most appropriate postoperative rehabilitation protocol following anterior cruciate ligament reconstruction with concomitant articular cartilage lesions: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2018;26(4):1065–73.
9. Wilk KE, Arrigo CA. Rehabilitation principles of the anterior cruciate ligament reconstructed knee: twelve steps for successful progression and return to play. Clin Sports Med. 2017;36(1):189–232.
10. Ellman MB, Sherman SL, Forsythe B, LaPrade RF, Cole BJ, Bach BR Jr. Return to play following anterior cruciate ligament reconstruction. J Am Acad Orthop Surg. 2015;23(5):283–96.
11. Petersen W, Taheri P, Forkel P, Zantop T. Return to play following ACL reconstruction: a systematic review about strength deficits. Arch Orthop Trauma Surg. 2014;134(10):1417–28.
12. Wright RW, Magnussen RA, Dunn WR, Spindler KP. Ipsilateral graft and contralateral ACL rupture at five years or more following ACL reconstruction: a systematic review. J Bone Joint Surg Am. 2011;93(12):1159–65.
13. Rodriguez-Roiz JM, Caballero M, Ares O, Sastre S, Lozano L, Popescu D. Return to recreational sports activity after anterior cruciate ligament reconstruction: a one- to six-year follow-up study. Arch Orthop Trauma Surg. 2015;135(8):1117–22.
14. Busfield BT, Kharrazi FD, Starkey C, Lombardo SJ, Seegmiller J. Performance outcomes of anterior cruciate ligament reconstruction in the National Basketball Association. Arthroscopy. 2009;25(8):825–30.

15. Erickson BJ, Harris JD, Cole BJ, Frank RM, Fillingham YA, Ellman MB, et al. Performance and return to sport after anterior cruciate ligament reconstruction in National Hockey League players. Orthop J Sports Med. 2014;2(9):2325967114548831.
16. Erickson BJ, Harris JD, Fillingham YA, Cvetanovich GL, Bhatia S, Bach BR Jr, et al. Performance and return to sport after anterior cruciate ligament reconstruction in X-games skiers and snowboarders. Orthop J Sports Med. 2013;1(6):2325967113511196.
17. Shah VM, Andrews JR, Fleisig GS, McMichael CS, Lemak LJ. Return to play after anterior cruciate ligament reconstruction in National Football League athletes. Am J Sports Med. 2010;38(11):2233–9.
18. Brophy RH, Gill CS, Lyman S, Barnes RP, Rodeo SA, Warren RF. Effect of anterior cruciate ligament reconstruction and meniscectomy on length of career in National Football League athletes: a case control study. Am J Sports Med. 2009;37(11):2102–7.
19. Failla MJ, Logerstedt DS, Grindem H, Axe MJ, Risberg MA, Engebretsen L, et al. Does extended preoperative rehabilitation influence outcomes 2 years after ACL reconstruction? A comparative effectiveness study between the MOON and Delaware-Oslo ACL cohorts. Am J Sports Med. 2016;44(10):2608–14.
20. Kaeding CC, Aros B, Pedroza A, Pifel E, Amendola A, Andrish JT, et al. Allograft versus autograft anterior cruciate ligament reconstruction: predictors of failure from a MOON prospective longitudinal cohort. Sports Health. 2011;3(1):73–81.
21. Kraeutler MJ, Bravman JT, McCarty EC. Bone-patellar tendon-bone autograft versus allograft in outcomes of anterior cruciate ligament reconstruction: a meta-analysis of 5182 patients. Am J Sports Med. 2013;41(10):2439–48.
22. Pallis M, Svoboda SJ, Cameron KL, Owens BD. Survival comparison of allograft and autograft anterior cruciate ligament reconstruction at the United States Military Academy. Am J Sports Med. 2012;40(6):1242–6.
23. Spencer JD, Hayes KC, Alexander IJ. Knee joint effusion and quadriceps reflex inhibition in man. Arch Phys Med Rehabil. 1984;65(4):171–7.
24. Albright JC, Crepeau AE. Functional bracing and return to play after anterior cruciate ligament reconstruction in the pediatric and adolescent patient. Clin Sports Med. 2011;30(4):811–5.
25. Gatewood CT, Tran AA, Dragoo JL. The efficacy of post-operative devices following knee arthroscopic surgery: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2017;25(2):501–16.
26. Dingenen B, Janssens L, Claes S, Bellemans J, Staes FF. Lower extremity muscle activation onset times during the transition from double-leg stance to single-leg stance in anterior cruciate ligament reconstructed subjects. Clin Biomech (Bristol, Avon). 2016;35:116–23.
27. Grooms DR, Page SJ, Onate JA. Brain activation for knee movement measured days before second anterior cruciate ligament injury: neuroimaging in musculoskeletal medicine. J Athl Train. 2015;50(10):1005–10.
28. Kapreli E, Athanasopoulos S, Gliatis J, Papathanasiou M, Peeters R, Strimpakos N, et al. Anterior cruciate ligament deficiency causes brain plasticity: a functional MRI study. Am J Sports Med. 2009;37(12):2419–26.
29. Davies GJ, McCarty E, Provencher M, Manske RC. ACL return to sport guidelines and criteria. Curr Rev Musculoskelet Med. 2017;10(3):307–14.
30. Rambaud AJM, Ardern CL, Thoreux P, Regnaux JP, Edouard P. Criteria for return to running after anterior cruciate ligament reconstruction: a scoping review. Br J Sports Med. 2018;52(22):1437–44.
31. Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. Arthroscopy. 2011;27(12):1697–705.
32. Brumitt J, Heiderscheit BC, Manske RC, Niemuth P, Mattocks A, Rauh MJ. The lower-extremity functional test and lower-quadrant injury in NCAA division III athletes: a descriptive and epidemiologic report. J Sport Rehabil. 2016;25(3):219–26.
33. Coronado RA, Bird ML, Van Hoy EE, Huston LJ, Spindler KP, Archer KR. Do psychosocial interventions improve rehabilitation outcomes after anterior cruciate ligament reconstruction? A systematic review. Clin Rehabil. 2018;32(3):287–98.
34. Hsu CJ, Meierbachtol A, George SZ, Chmielewski TL. Fear of reinjury in athletes. Sports Health. 2017;9(2):162–7.
35. Morrey MA, Stuart MJ, Smith AM, Wiese-Bjornstal DM. A longitudinal examination of athletes' emotional and cognitive responses to anterior cruciate ligament injury. Clin J Sport Med. 1999;9(2):63–9.
36. Mainwaring LM, Hutchison M, Bisschop SM, Comper P, Richards DW. Emotional response to sport concussion compared to ACL injury. Brain Inj. 2010;24(4):589–97.
37. Christino MA, Fantry AJ, Vopat BG. Psychological aspects of recovery following anterior cruciate ligament reconstruction. J Am Acad Orthop Surg. 2015;23(8):501–9.
38. Webster KE, Feller JA, Lambros C. Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. Phys Ther Sport. 2008;9(1):9–15.

Return to Sport After Primary ACL Reconstruction in Amateur, Children, and Elite Athletes: Feasibility and Reinjury Concerns

6

Sue Barber-Westin and Frank R. Noyes

6.1 Introduction

This chapter summarizes return to sport (RTS) and subsequent reinjury/failure data after anterior cruciate ligament (ACL) reconstruction from a total of 95 studies (published from 2000 to 2018) that reported on 42,275 athletes (Table 6.1). Three major categories of subjects are presented: amateur athletes of all ages (29,711 athletes from 40 studies), children and adolescent athletes (10,661 athletes from 31 studies), and elite collegiate and professional athletes (1903 athletes from 23 studies). One study that provided epidemiologic data on recurrent ACL ruptures in collegiate athletes was also included [1]. For each athlete category, we summarize (when available) RTS rates, factors that had either a positive or negative influence on postoperative sports activity levels, ACL reinjury rates (to either knee), significant factors associated with ACL reinjury rates, and published criteria cited by the studies for release to unrestricted activities.

Acknowledgement is made that no scientific evidence is presently available to determine when an ACL graft has gained the appropriate biomechanical strength indices to be safely subjected to high forces incurred with athletics. The process of ligamentization occurs over a lengthy period of time and differs according to the graft source selected for reconstruction [2]. These concepts are discussed further in Chap. 7.

The methods for rating athletic activities and determination of RTS percentages varied in these studies and this presents problems when comparing published data. Validated sports activity scales such as the International Knee Documentation Committee (IKDC), Tegner, Cincinnati, and Marx were used in the majority of studies. The published reliability, validity, and responsiveness properties of these scales, as well as their potential pitfalls, are detailed in Chap. 23. However, non-validated questionnaires developed by study investigators were also used in many studies and these instruments were seldom provided in the publications. Few studies indicated whether patients who returned to sports did so with or without symptoms or limitations due to the knee condition [3–5]. We believe that RTS data should include an analysis of any problems athletes experience either during or after participation and the number of so-called knee abusers [6] should be provided. Finally, the follow-up time period of data collection varied from 1 to 20 years postoperatively. Caution is therefore warranted in the interpretation of the RTS data presented for various categories of athletes.

In addition to the individual studies included in this chapter, meta-analyses and studies from

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_6

Table 6.1 Summary of number of studies and patients reviewed

	All studies reviewed		RTS and reinjury data		RTS data		Reinjury data	
	No. of studies	No. of patients	No. of studies	No. of patients	No. of studies	No. of patients	No. of studies	No. of patients
Amateur athletes	40	29,711	12	2118	33	8331	17	23,267
Children/ adolescent athletes	31	10,661	25	2099	27	2307	29	10,453
Collegiate athletes	5	377[a]	1	89	4	342	2	89[a]
Professional athletes	19	1526	9	969	19	1526	9	969

RTS return to sport
[a]The study by Gans et al. [1] did not provide the number of patients

national ACL registries have calculated ACL graft and contralateral ACL reinjury rates linked to RTS and factors significantly associated with reinjuries. Wiggins et al. [7] assessed data from 19 studies on 23,740 subjects (mean age, 24.4; range, 11–64) and calculated reinjury rates to the ipsilateral ACL of 7% (95% confidence interval [CI] 5–8%), to the contralateral ACL of 8% (95% CI 5–13%), and to either knee of 15% (95% CI 10–22%). Factors associated with reinjuries were age <25 years (reinjury rate 20%), return pivoting/cutting sports (reinjury rate 21%), and both age <25 years and return pivoting/cutting sports (reinjury rate 23%). Faltstrom et al. [8] examined data from 20,824 patients (all ages) in the Swedish national ACL registry of whom 702 (3%) required ACL revision and 591 (3%) sustained a contralateral tear. These investigators reported significant predictors for ACL reinjuries were age <16 years (hazard ratio [HR] 4.26, $P < 0.001$), primary ACL reconstruction within 1 year (HR 1.5, $P < 0.001$), and playing soccer at primary injury (HR 1.00, $P < 0.05$). Kay et al. [9] reviewed data from 20 studies of 717 patients aged 6–19 years. The reinjury rates were 13% to the ipsilateral ACL and 14% to the contralateral ACL. These authors found that few studies assessed factors associated with reinjuries.

Also not included in the analyses in this chapter, but important to note, are a few studies that examined RTS rates after bilateral primary ACL reconstructions [10–13]. Webster et al. [13] followed 107 patients a mean of 5.3 years after the most recent ACL reconstruction, all of whom were involved in level I or II sports before their first ACL injury. After the first ACL procedure, 83% returned to the same sports level; however after the second ACL reconstruction, only 40% returned to the same level. There was no significant effect of age, gender, or time between ACL procedures on RTS. Of those that did not return, nearly half cited fear of reinjury as the predominant reason. Faltstrom et al. [10] reported poorer results in 83 patients that had bilateral ACL reconstructions. After the first ACL reconstruction, 75% returned to the previous Tegner activity level; however, after the second procedure, only 12% returned to their prior activity level. The majority cited reduced function of the knee(s) as the major reason for not returning.

In 2011, we performed a systematic review that analyzed the factors investigators had used over the previous 10 years to determine when return to unrestricted athletics after ACL reconstruction was allowed [14]. Of 264 studies in the review, 105 (40%) failed to provide any RTS criteria. Only 35 studies (13%) noted objective criteria required for RTS. We recommended a comprehensive knee examination by the surgeon followed by a battery of tests that include an isokinetic lower limb strength assessment, single-leg hops, knee arthrometer, video drop-jump, and single-leg squat prior to release to unrestricted activities. In addition, hip and core muscle strength testing and the multistage fitness test were recommended. Others have also recommended several tests and provided criteria for RTS [15–19].

The updated material in this chapter regarding this topic continues to show that many publications fail to provide RTS criteria, even in articles in which the determination of return to preinjury activity levels was a main purpose of the study. For instance, in the 30 studies on amateur athletes, 16 did not provide any RTS criteria and 3 provided just one criteria. We speculate that the published high reinjury rates in young athletes are due to a multitude of factors. Of particular concern is whether normal muscular and neuromuscular indices have been achieved bilaterally before RTS is allowed. We acknowledge that some of the studies that did not provide RTS criteria may indeed have had certain objective measures athletes had to pass before release to full sports, but did not include this information in the publication.

6.2 Amateur Athletes

6.2.1 Return to Sport: Rates and Influential Factors

RTS data for 8445 amateur athletes aged 11–59 (approximate mean age, 26 years) are shown in Table 6.2 and Fig. 6.1 [3–5, 20–50]. The percentages of patients that returned to preinjury levels after ACL reconstruction ranged from 30% to 64% at 1 year postoperatively, from 36% to 91% at 2–4.7 years, from 16% to 74% at 5–7 years, and from 30% to 79% at 15–20 years. One long-term study [23] (mean, 19.7 years) reported that 79% of the patients had returned to their preinjury level at any time and, at the final evaluation, 61% were participating in strenuous or very strenuous sports. Another long-term study [24] (mean, 15 years) reported that 73% of the patients had returned to their preinjury sport level at any time postoperatively; however, the percent participating at this level at final follow-up was not given. A third long-term study [51] (mean, 15 years) provided percentages of patients participating in jumping/pivoting sports; however, it was unknown how many returned to their preinjury activity level.

Noteworthy declines in return to preinjury activity levels were noted in two studies that compared RTS rates at different postoperative time periods. Smith et al. [3] reported that although 56% of 77 patients (37 male, 40 female, mean age 21 years) returned to preinjury activity levels 1 year postoperatively, only 36% were still participating a mean of 3.6 years postoperatively. Brophy et al. [25] found that 61% of 100 soccer players (55 male, 45 female, mean age 24.2 years) returned to their preinjury or higher level of play a mean of 1 year postoperatively. However, at long-term follow-up (mean 7.2 years), only 16% were still participating at their preinjury level.

Faltstrom et al. [50] followed 117 female soccer players who underwent ACL hamstring reconstruction a mean of 3.7 years postoperatively. Although all returned to soccer after surgery (61% same level, 18% higher level, 21% lower level), at follow-up 62% had stopped playing the sport. The most common reason was a new knee injury, which occurred in 26 players (36%).

Failla et al. [27] compared return to preinjury sport rates between two cohorts: the Delaware-Oslo ACL (DOC, 192 patients) Cohort and the Multicenter Orthopaedic Outcomes Network (MOON, 1995 patients) group. The DOC group underwent extended preoperative rehabilitation and the authors hypothesized that this group would have superior outcomes. At 2 years postoperatively, 72% of DOC patients returned to preinjury activity levels compared with 63% of those in the MOON cohort ($P < 0.001$). The concept of the effectiveness of extended preoperative rehabilitation before ACL reconstruction is further detailed in Chaps. 7 and 8.

The factors that influenced RTS are summarized in Table 6.3. The most frequently studied individual factors were age, gender, postoperative muscle strength, postoperative limb symmetry, and preoperative body mass index (BMI). Results were mixed with regard to the effect of these factors on RTS rates. Several investigations used multivariate analyses to determine factors predictive of RTS. For instance, Nawasreh et al. [22] reported a significant relationship between scores on return-to-activity criteria testing and return to preinjury activity levels in 80 patients determined 1 and 2 years postoperatively. Patients who scored ≥90% (at 6 months postoperative) on four single-leg hop tests, an isometric quadriceps strength test, the Knee Injury and Osteoarthritis Outcome-

Table 6.2 Return to sport after primary ACL reconstruction in amateur athletes

Study	Cohort			Preinjury sports and scales	Criteria to return to sport	Return to sport percentages	Return to sport factors
	No. of men, women	Mean age (range)	Mean follow-up year				
Salmon et al. [23]	75, 74	28 (19–52)	19.7 (17.7–21.4)	NP	≥ 6 months clinical confirmation ligament stability by surgeon	80% preinjury level at any time; current f.u. 61% strenuous/very strenuous, 24% moderate, 15% light sports	NP
Bourke et al. [24]	432, 241	29 (13–62)	15	NP	6–9 months when rehabilitation goals met	73% preinjury level at any time	NP
Allen et al. [26]	0, 180	19.6 (NP)	5.7	Soccer 50% Other sports 50%	Patient gained functional stability, symmetric lower extremity strength	74% soccer players returned competitive soccer All other athletes returned sport, unknown if same as preoperative level	NP
Takazawa et al. [20]	110, 0	NP (17–25)	4.7	Rugby 100%	NP	91% preinjury level	NP
Grindem et al. [21] DOC	46, 54	24.3 (NP)	2	IKDC level I or II sports ≥2×/week	<10% deficit for isometric quadriceps strength, limb symmetry four single-leg hop tests; >90% scores KOOS-ADLS, GRS	89% preinjury (level I group)	NP
Webster et al. [47]	36, 11	41 (18–40)	15.3	Cincinnati Sports Activity Scale	NP	BPTB graft group: 44.5% jumping, pivoting; 44.5% running, twisting; 11% low-impact Hamstring graft group: 18% jumping, pivoting; 59% running, twisting; 23% low-impact	NP
Brophy et al. [25] MOON	55, 45	24.2 (11–53)	1 and 7.2	Soccer 100%	NP	1 year: 61% preinjury soccer 7.2 years: 16% preinjury soccer	Positive effect: male gender Negative effect: age ≥30
Laboute et al. [30]	234, 64	25 (16–53)	4	Soccer, skiing, handball, rugby	NP	66% preinjury level, 20% lower level	NP

Ardern et al. [33]	76, 46	28.3 (15–60)	2	Australian football, soccer, netball, basketball	NP	41% preinjury level	NP
Noyes and Barber-Westin [48]	68, 19	27 (NP)	2.3	Cincinnati Sports Activity Scale	Completion of running program, no pain, swelling, giving way, <3 mm increase in anteroposterior translation on knee arthrometer testing, 6–9 months	60% preinjury level or higher, 17% decreased, 8% playing with symptoms, 8% no sports due to knee condition, 7% no sports non-knee-related	NP
Nawasreh et al. [22]	80 total	NP (15–55)	1 and 2	IKDC level I or II sports ≥50 h/year	<10% deficit for isometric quad strength, limb symmetry four single-leg hop tests; >90% scores KOOS-ADLS, GRS	1 year: 81% patients who passed RTS criteria, 44% patients who failed RTP criteria, 61% overall 2 years: 84% patients who passed RTS criteria, 46% patients who failed RTP criteria, 67% overall	Positive effect: limb symmetry four single-leg hop tests
Smith et al. [3]	37, 40	21 (15–30)	1 and 3.6	Cincinnati Sports Activity Scale, competitive athletes	NP	1 year: 56% preinjury level with no problems 3.6 years: 36% preinjury level with no problems	No effect: gender
Failla et al. [27] MOON and DOC	1183, 1004	24 (NP)	2	NP	DOC: <10% deficit for isometric quad strength, limb symmetry four single-leg hop tests; >90% scores KOOS-ADLS, GRS MOON: <15% deficit for four single-leg hop tests, ≥ 9 IKDC GRKF, no functional complaints, confidence running, cutting, jumping at full speed	DOC 72%, MOON 63% preinjury level ($P < 0.001$)	Positive effect: preoperative rehabilitation
Almeida et al. [28]	131, 45	32.6 (13–54)	2.9	NP	6 months for sports movements, 8 months for contact sports	69% preinjury level	Positive effect: age <30 years No effect: gender, BMI, injury associated with trauma

(continued)

Table 6.2 (continued)

Study	Cohort			Preinjury sports and scales	Criteria to return to sport	Return to sport percentages	Return to sport factors
	No. of men, women	Mean age (range)	Mean follow-up year				
Beischer et al. [29]	44, 19	NP (21–30)	1	Tegner ≥6	NP	63% Tegner ≥6	NP
Lefevre et al. [31]	333, 164	30.1 (15–50)	1	65% pivoting contact, 21% pivoting noncontact, 14% nonpivoting	NP	64% usual sport, 91% any sport, 24% same or better level of play	Positive effect: played competitive or pro sport, IKDC Subjective score at 6 months >75, no complications, higher KOOS QoL scores No effect: BMI, concomitant cartilage injury
Ardern et al. [32]	183, 131	32.5 (NP)	3.3	Australian FB (26%), netball (21%), basketball (14%), soccer (12%)	Completion rehab program, full ROM, stable knee, functional quad control, no effusion	61% preinjury level, 32% lower level, 7% no sports	Positive effect: age <25 years No effect: Gender
Rosso et al. [34]	141, 35	29.5 (15–55)	3.7	NP	<15% deficit isokinetic quad and ham strength, <10% deficit single-leg hop, clinical knee stability, no pain or effusion	58% preinjury level, 32% lower level, 10% no sports	Positive effect: rehab >3months, use of on-field rehabilitation Negative effect: ACL-RSI < 60% No effect: age, gender, time injury to surgery, KT-1000

Hamrin Senorski et al. [35]	134, 138	25 (NP)	1	Tegner ≥6	NP	57% Tegner ≥6; 63% men, 51% women	Positive effect: male gender, age 12–24, pre-op Tegner level 10 Negative effect: age 35–58, meniscus injury, articular cartilage injury, MCL injury No effect: BMI, LCL injury, hamstring or BPTB graft
Lentz et al. [36]	60, 34	22.4 (15–50)	1	Tegner ≥5	Full ROM, <15% deficit quad isokinetic strength, no effusion, completion agility and sport-specific program	55% preinjury	Positive effect: lower-grade knee joint effusion, fewer episodes knee instability, lower knee pain, higher quadriceps peak torque-body wt ratio, IKDC subjective score >93, lower TSK-11 scores No effect: age
Novaretti et al. [37]	47, 11	34.5 (NP)	1	Tegner ≥5	NP	53% preinjury, 84% any sport	No effect: 6 months p.o. quadriceps and hamstrings isokinetic strength, postural stability, drop-jump test normalized knee separation distance

(continued)

Table 6.2 (continued)

Study	Cohort			Preinjury sports and scales	Criteria to return to sport	Return to sport percentages	Return to sport factors
	No. of men, women	Mean age (range)	Mean follow-up year				
Sousa et al. [38]	92, 131	22 (12–59)	4	Tegner	<15% deficit isokinetic quad and ham strength, <10% deficit three single-leg hop tests	52% preinjury Tegner level	Positive effect: use of an autograft vs. allograft, <15% deficit isokinetic muscle strength, <10% deficit single-leg hop limb symmetry
Rodriguez-Roiz et al. [39]	74, 25	30 (14–52)	3	Tegner 5–7	NP	51% preinjury, 40% lower level, 9% no sports	Positive effect: female gender, return low-impact sports, motivation to return Negative effect: fear reinjury No effect: BMI, age
Langford et al. [40]	55, 32	27.5 (18–40)	1	Level 1 or 2 weekly Cincinnati Sorts Activity Scale	NP	51% full competition	Positive effect: higher ACL-RSI scale scores No effect: age, time from injury to surgery, single-leg hop, ERAIQ scores
Mascarenha et al. [4]	20, 26	18	5	IKDC level I or II sports 4–7 times/ week	At 6 months if no effusion, full ROM, <10% deficit muscle strength	50% preinjury, 50% lower level, 17% participating with instability symptoms	No effect: graft (hamstring or BPTB)
Devgan et al. [41]	44, 4	23.6 (20–28)	5	Tegner	Close to full ROM and muscle strength	46% preinjury level, 37% lower level, 17% no sports	Negative effect: symptoms (pain, instability), fear reinjury

Dunn et al. [42] MOON	222, 171	23 (NP)	2	Marx, basketball (24%), soccer (18%), football (15%), others (26%)	NP	45% preinjury level	Positive effect: higher baseline activity level, lower baseline BMI. Negative effect: female gender, smoking, revision ACL
Sandon et al. [43]	250, 116	23 (NP)	3.2	Soccer 100%	NP	36% preinjury soccer level, 18% lower level, 46% no return	Positive effect: male gender, BPTB graft (compared with hamstring), no associated cartilage injury Negative effect: knee pain with activity No effect: age, quadriceps or hamstrings muscle strength
Ardern et al. [44]	340, 163	27.2 (NP)	1	Cincinnati Sports Activity Scale Australian football (39%), netball (24%)	Completion rehab program, full ROM, stable knee, functional quad control, no effusion	33% preinjury level, 34% lower level, 33% no sports	Positive effect: male gender, hop test symmetry ≥85%, patients playing seasonal sports No effect: IKDC A-B rating

(continued)

Table 6.2 (continued)

Study	Cohort			Preinjury sports and scales	Criteria to return to sport	Return to sport percentages	Return to sport factors
	No. of men, women	Mean age (range)	Mean follow-up year				
Faltstrom et al. [45]	0, 182	20 (16–25)	1.5	Soccer 100%	NP	30% preinjury soccer level, 11% higher level, 10% lower level	Positive effect: shorter time injury to surgery, no smoking, motivation to return to soccer, higher SMPS personal standards score, belief in role of PT No effect: age, mechanism injury, concomitant meniscus injury, SSP score, SMPS scores (except personal standards)
Faltstrom et al. [50]	0, 117	19.9 (16–25)	3.7	Soccer 100%	NP	61% preinjury soccer level, 18% higher level, 21% lower level	NP
Hamrin Senorski et al. [46]	80, 77	NP (15–30)	1	Tegner ≥6	NP	33% Tegner ≥6 (± 1 level); 36% men, 30% women	Positive effect: quadriceps strength for women, higher knee self-efficacy scores No effect: hamstring strength, single-leg hop distance

Nwachukwu et al. [5]	120, 112	26.7 (14–65)	3.7	Basketball, football, lacrosse, soccer, tennis, or skiing ≥4 day/week	NP	89% preinjury levels 44% no problems with sports, 23% some pain, 25% limited performance, 8% no sports	Positive effect: BPTB autograft (compared with hamstring and allografts) Negative effect: soccer or lacrosse preinjury, fear reinjury No effect: Age, gender, ethnicity
Barber-Westin et al. [49]	47, 47	29 (15–54)	2.2	Cincinnati Sports Activity Scale	Completion of running program, no pain, swelling, giving way, <3 mm increase in anteroposterior translation on knee arthrometer testing, 6–9 months	57% preinjury level or higher, 22% decreased, 4% playing with symptoms, 4% no sports due to knee condition, 13% no sports non-knee related	No effect gender

ACL-RSI ACL Return to Sport After Injury scale, *ADLS* activities of daily living score, *BMI* body mass index, *BPTB* bone-patellar tendon-bone, *DOC* Delaware-Oslo ACL Cohort, *ERAIQ* Emotional Response to Athletes to Injury Questionnaire, *GRKF* Global Rating of Knee Function, *GRS* Global Rating Score, *IKDC* International Knee Documentation Committee, *KOOS* knee injury and osteoarthritis outcome, *LCL* lateral collateral ligament, *MCL* medial collateral ligament, *MOON* Multicenter Orthopaedic Outcomes Network, *NP* not provided, QoL, quality of life, *ROM* range of motion, *RTS* return to sport, *SSP* Swedish Universities Scales of Personality, *SMPS* Sport Multidimensional Perfectionism Scale *TSK* Tampa Scale for Kinesiophobia

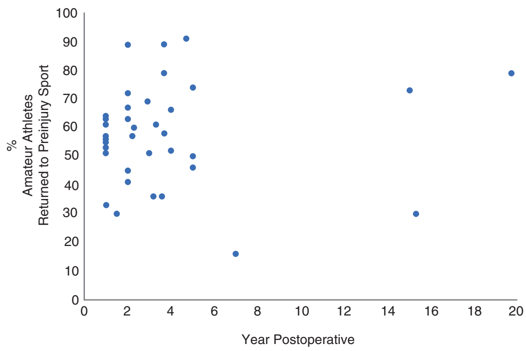


Fig. 6.1 Data from 34 studies that followed 8445 amateur athletes are shown regarding the percent who returned to preinjury sports activities after ACL reconstruction

Activities of Daily Living (KOOS-ADL) scale, and the Global Rating Score were placed into a *pass* group and those who failed any of these criteria were placed in a *fail* group. At 1 year postoperatively, 81% returned to preinjury activity levels in the pass group compared with 44% in the fail group. Similar results were reported at 2 years postoperatively. The multivariate logistic regression model showed the combination of age, gender, and limb symmetry (from the four hop tests) significantly predicted the ability to return to preinjury activity levels ($R^2 = .45$, $P < 0.001$).

Brophy et al. [25] reported their multivariate regression model (factors entered: age, gender,

Table 6.3 Summary of factors affecting return to sport after ACL reconstruction in amateur athletes

	Effect on RTS (no. of studies)			Total no. of
Factor	Positive	Negative	None	studies
Age	2 (<25 years), 1 (<30 years)	1 (35–58 years), 1 (≥30 years)	9	14
Gender	4 (male), 1 (female)	1 (female)	6	12
Preoperative				
Body mass index	1 (“lower”)		4	5
Mechanism of injury			2	2
No smoking	2			2
Surgical				
Associated cartilage injury	1 (none)	1 (yes)	1	3
Shorter time from injury to surgery	1		2	3
Associated MCL injury		1		1
Associated LCL injury			1	1
BPTB vs. hamstring autograft	1		2	3
BPTB autograft vs. hamstring autograft or allograft	1			1
Any autograft vs. allograft	1			1
ACL revision vs. primary		1		1
Associated meniscus injury		1	1	2
No complications	1			1
Ethnicity			1	1
Rehabilitation				
Use of preoperative rehabilitation	1			1
Use of postoperative rehabilitation >3 months	1			1
Use of on-field end-stage rehabilitation	1			1
Belief in role of physical therapist in RTS	1			1
Type of sport: preinjury				
Competitive or professional sport	1			1
Tegner level 10	1			1
“Higher” activity level	1			1
Soccer or lacrosse		1		1

Table 6.3 (continued)

Factor	Effect on RTS (no. of studies)			Total no. of studies
	Positive	Negative	None	
Type of sport returned to	1 (seasonal), 1 (low impact)			2
Postoperative lower-grade knee joint effusion	1			1
Postoperative objective tests				
Muscle strength	1 (<15% deficit isokinetic), 1 ("quadriceps strength") 1 (quadriceps strength in women)		3	6
Single-leg hop tests <10–15% deficit	3		2	5
Normalized knee separation distance drop-jump			1	1
Postural stability			1	1
KT-1000 anteroposterior displacement			1	1
Postoperative symptoms				
Knee instability	1 (fewer episodes)			1
Knee pain with activity	1 ("lower level")	1 (with activity)		2
Any symptoms		1		1
Psychological factors				
Fear of reinjury		3		3
High motivation to return to sport	2			2
Higher ACL-RSI scores	1 ("higher")	1 (<60%)		2
Lower TSK-11 scores	1			1
Higher Knee Self-Efficacy scores	1			1
Higher SMPS personal standards scores	1			1
SMPS scores (except personal standards)			1	1
ERAIQ scores			1	1
SSP score			1	1
IKDC Knee Evaluation form grades A–B			1	1
IKDC Subjective Knee Evaluation form	1 (>75 pts. 6 months p.o.), 1 (>93 pts. 12 months p.o.)			2
KOOS quality of life higher scores	1			1

ACL-RSI ACL Return to Sport after Injury scale, *BPTB* bone-patellar tendon-bone, *ERAIQ* Emotional Responses of Athletes to Injury Questionnaire, *IKDC* International Knee Documentation Committee, *KOOS* Knee Injury and Osteoarthritis Outcome Score, *LCL* lateral collateral ligament, *MCL* medial collateral ligament, *pts* points *RTS* return to sport, *SMPS* Sport Multidimensional Perfectionism Scale, *SSP* Swedish Universities Scales of Personality, *TSK* Tampa Scale for Kinesiophobia

graft type) was unable to predict RTS a mean of 7.2 years postoperatively. Lefevre et al. [31] reported that five variables were significantly and positively associated with RTS: primary ACL reconstruction (versus revision, odds ratio [OR] 2.0, $P = 0.02$), professional or competitive sport (versus recreational sport, OR 2.2, $P < 0.0001$), subjective IKDC score at 6 months >75 (OR 2.1, $P = 0.001$), KOOS Quality of Life score at 6 months >60 (OR 1.7, $P = 0.009$), and absence of complications or reinjury (OR 2.6, $P = 0.03$). Rosso [34] found just 1 variable was significantly associated with RTS: postoperative rehabilitation lasting more than 3 months (OR 13.16, $P = 0.005$). An ACL-Return to Sport After Injury (ACL-RSI) score of <60 was predictive of the inability to RTS (OR 0.04, $P = 0.0001$).

Multivariable analyses reported by Hamrin Senorski et al. [35] found an increase in the odds of RTS for male gender (OR 2.58, P = 0.002), higher preoperative Tegner activity level (OR 1.45, P = 0.004), <25 years of age at surgery (OR 2.32, P < 0.0001), no concomitant medial collateral ligament injury (OR 7.61, P = 0.02), and no meniscal injury (medial or lateral, OR 1.92, P < 0.05). Factors not predictive included BMI, autograft choice, and concomitant articular cartilage injury. Nwachukwu et al. [5] reported their multivariable analysis found an increase in the odds of RTS with use of a patellar tendon autograft (versus allograft, OR 5.63, P = 0.02). Conversely, the odds of RTS were significantly decreased for patients who had played soccer (OR 0.23, P = 0.008) or lacrosse (OR 0.24, P < 0.05).

6.2.2 Reinjuries: Rates and Significant Factors

Reinjury rates in amateur athletes attributed to RTS from 18 studies are shown in Table 6.4 [20, 21, 23–26, 30, 33, 47–50, 52–57]. Overall, ACL graft reinjury rates averaged 9% (range, 1–25%, Fig. 6.2). Reinjury rates according to graft source ranged from 2% to 7% for BPTB (5 studies), from 4% to 25% for STG (5 studies), and from 2% to 11% from cohorts that included patients who received either BPTB or STG autografts (6 studies). Only one study reported an allograft reinjury rate (6.9%).

Contralateral ACL injury rates, provided in 13 studies, averaged 9% (range, 0–20%). With all studies included, these rates were not associated with longer follow-up. However, when the 20% rate reported by Paterno et al. [52] was eliminated from the analysis, a significant association was found (R^2 = 0.49, P = 0.008). Reinjuries to either knee occurred in an average of 17% (range, 5–32%, Fig. 6.3). Significant factors associated with reinjury rates are summarized in Table 6.5. Return to sport involving cutting and pivoting was the most common risk factor for both the ACL-reconstructed and the contralateral knee.

6.2.3 Published Criteria for Release to Unrestricted Activities

Criteria published by the articles that focused on amateur athletes for release to full unrestricted sports activities are shown in Table 6.6. Nine studies provided objective measurable criteria, of which three were from the Delaware-Oslo ACL Cohort. We acknowledge that some of the studies that did not provide RTS criteria may indeed have had certain objective measures athletes had to pass before release to full sports, but did not include this information in the publication.

6.2.4 Conclusions and Recommendations

The data analyzed from the 40 studies on amateur athletes show a wide range of RTS percentages, with very little information regarding specific sports and levels (for instance, high school soccer or recreational league tennis). A noteworthy problem with these studies is that they typically included patients of all ages, from adolescents to middle-aged adults, who have varying interests, motivations, and lifestyle commitments that allow participation in athletics. An average of 57% of patients returned to preinjury sport levels (range, 16–91%). The majority of studies reported ACL graft failure rates ≤10%; however, contralateral ACL ruptures appear to be of equal or even greater concern upon return to athletics. Note is made that failure rates were reported in only 18 studies for the ACL graft and in 14 studies for the contralateral ACL. The most common factor related to reinjury of either knee was the RTS that require cutting and pivoting. Before release to high-risk sports involving extensive cutting, pivoting, jumping, twisting, and turning, we conduct a battery of tests that measure lower limb strength, function and dynamic stability, anterior tibial translation, and neuromuscular function (described further in Chaps. 20 and 21). Using these criteria, our studies reported ACL graft failure rates of 5% [49] to 7% [48], with no contralateral ACL injuries. End-stage rehabilitation is individualized based on the

Table 6.4 Reinjury/failure rates upon return to sport after ACL reconstruction in amateur athletes

Study	Mean follow-up year	Primary ACL reconstruction graft (no.)[a]	Reinjury/failure rates			Sports comments[b]	Other factors associated with reinjuries/failures[b]	
			ACL-R knee[b]	ACL-C knee	Either knee		ACL-reconstructed knee	Contralateral knee
Faltstrom et al. [50]	3.7	Hamstring (117)	25%	NA	NA	All soccer players, increased odds ACL graft tear compared with control group soccer players (HR 4.8, $P < 0.001$)	None	NP
Salmon et al. [23]	20	Hamstring (126)	20%	12%	32%	Nearly all reinjuries to either knee associated with sports	Posterior tibial slope ≥ 12° (HR 3.0, $P = 0.001$)	Posterior tibial slope ≥ 12° (HR 6.7, $P = 0.001$)
Bourke et al. [24]	15	Hamstring, BPTB (673)	11%	12%	23%	Return preinjury sport increased odds contralateral ACL injury (HR 2.5, $P = 0.003$)	Male gender (HR 2.1, $P = 0.007$), family history (HR 1.8, $P < 0.05$)	Family history (HR 1.7, $P < 0.05$)
Allen et al. [26]	5.7	BPTB, hamstring (180)				Soccer players significantly more ACL graft tears and contralateral ACL tears ($P < 0.01$) than other athletes	Soccer group OR 1.5× risk for failure with every year of increased age ($P < 0.05$)	None
		Soccer players	11%	17%	28%			
		All other athletes	1%	4%	5%			
Takazawa et al. [20]	4.7	Hamstring and Telos artificial ligament (110)	16%	7%	24%	All patients rugby players, all reinjuries during rugby	None	None
Grindem et al. [21]	2	BPTB, hamstring (100)	8%	2%	10%	Return to level I sports <9 months post-op 4.32 times higher reinjury rate than other sport levels ($P < 0.05$)	Quadriceps strength deficit ($P < 0.05$)	None
Webster et al. [47]	15.3	Hamstring (25)	12%	8%	20%	Reinjuries traumatic	NP	NP
		BPTB (22)	4.5%	18%	23%			
Brophy et al. [25]	7.2	BPTB (69), hamstring (28), allograft (3)	3%	9%	12%	All patients soccer players, reinjuries during soccer	Female gender ($P = 0.03$)	Nondominant limb injured ($P = 0.03$)
Laboute et al. [30]	4	Hamstring (160), BPTB (138)	9%	NA	NA	Return sports ≤7 months postoperative ($P < 0.05$)	None	None
Ardern et al. [33]	2	Hamstring (122)	4%	2%	6%	Reinjuries associated with sports	Not assessed	Not assessed
Noyes and Barber-Westin [48]	2.3	BPTB (87)	7%	0%	7%	3 of 6 reinjuries during sports	None	None

(continued)

Table 6.4 (continued)

Study	Mean follow-up year	Primary ACL reconstruction graft (no.)[a]	Reinjury/failure rates			Sports comments[b]	Other factors associated with reinjuries/failures[b]	
			ACL-R knee[b]	ACL-C knee	Either knee		ACL-reconstructed knee	Contralateral knee
Paterno et al. [52]	2	BPTB, hamstring, allograft (78)	9%	20%	29%	All reinjuries noncontact, during pivoting, cutting sports	Female gender (compared with controls IRR 4.51, $P = 0.0004$)	None
Shelbourne et al. [53]	5	BPTB >18 years old (887)	2%	3%	5%	Reinjuries to either knee associated with basketball or soccer	None	Female gender ($P < 0.001$)
Webster et al. [54]	4.8	Hamstring (547) BPTB (14)	4.5%	7.5%	12%	Reinjuries associated with cutting, pivoting sports (ACL graft OR 3.9, $P = 0.01$; contralateral ACL OR 4.9, $P = 0.001$)	Age <20 years (OR 6.3, $P = 0.0001$), contact mechanism for injury (OR 3.2, $P = 0.005$), family history (OR 2.4, $P < 0.05$)	Family history (OR 2.2, $P < 0.05$)
Kaeding et al. [55]	2	BPTB (1131)	3.2%	NA	NA	Reinjuries associated with higher activity levels before surgery (OR 1.1, $P < 0.01$)	Allograft (OR 5.2, $P < 0.01$)	None
		Hamstring (891)	4.6%	NA	NA			
		Allograft (466)	6.9%	NA	NA			
		Total (2488)	4.4%	3.5%	8%			
Andernord et al. [56]	2	Hamstring, BPTB (16,930)	2%	NA	NA	Revision rates: soccer all males RR 1.58 ($P < 0.01$), all females RR 1.43 ($P < 0.05$); downhill skiing all males RR 0.24 ($P < 0.05$)	Age 13–19 males RR 2.67 ($P < .001$) and females RR 2.25 ($P < .001$), injured during soccer males RR 1.58 ($P < .01$) and females RR 1.43 ($P < .05$)	NA
Borchers et al. [57]	2	Autografts (135), allografts (187)	6.5%	NA	NA	Higher postoperative Marx activity score associated with reinjuries (OR 5.53, $P < 0.05$)	Allografts (OR 5.56, $P < 0.01$)	Not assessed
Barber-Westin et al. [49]	2.2	BPTB (94)	5%	0%	5%	No reinjuries	None	None

ACL anterior cruciate ligament, *ACL-R* anterior cruciate ligament –reconstruction, *ACL-C* anterior cruciate ligament contralateral, *BPTB* bone-patellar tendon-bone, *HR* hazard ratio, *IKDC* International Knee Documentations Committee, *IRR* incidence rate ratio, *KOOS-QOL* Knee Injury and Osteoarthritis Outcome-Quality of Life, *NA* not assessed, *NP* not provided, *OR* odds ratio, *RR* relative risk, *STG* semitendinosus-gracilis.

[a]Autograft unless otherwise indicated

[b]Statistical values given when provided in study

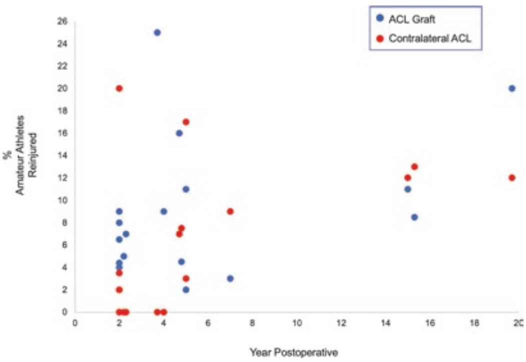


Fig. 6.2 Percentages of postoperative ACL injuries in amateur athletes are shown

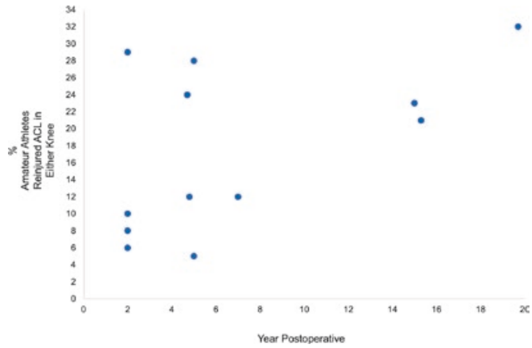


Fig. 6.3 Percentages of postoperative ACL injuries in either knee in amateur athletes are shown

Table 6.5 Summary of factors statistically associated with reinjury/failure rates after ACL reconstruction in amateur athletes

	ACL graft	Contralateral ACL
Factor	No. of studies	No. of studies
Return cutting, pivoting sports	9	6
Female gender	3	1
Family history ACL tear	2	2
Use of allograft	2	0
Higher postoperative Marx activity score	1	0
Return preinjury sport level	0	1
Higher preinjury activity levels	1	0
Return sports ≤7 months postoperative	1	0
Quadriceps strength deficit	1	0
Contact injury	1	0
Male gender	1	0
Posterior tibial slope ≥12°	1	1
Age <25	1	1
Nondominant limb injured	0	1

athlete's goals and is discussed in detail in Chaps. 13 to 18. We advise patients who wish to return to high-risk sports to undergo advanced neuromuscular retraining (Sportsmetrics), described in Chap. 14. We recommend the return to low-impact activities in patients with advanced articular cartilage damage. RTS recommendations for athletes under the age of 20 who appear to be at the highest risk of reinjury are provided in the next section of this chapter.

6.3 Children and Adolescent Athletes

6.3.1 Return to Sport: Rates and Influential Factors

RTS data for 2307 patients aged 6–19 from 27 studies are shown in Table 6.7 and Fig. 6.4 [20, 23, 29, 53, 58–80]. The percentages of patients returning to preinjury levels after ACL reconstruction ranged from 45% to 100% at 1–3 years postoperatively, from 40% to 92% at 4–5 years, from 69% to 87% at 6–10 years, and from 61% to 89% at 11–20 years. There was no relationship between the amount of time postoperatively data were collected and RTS percentages reported. Although 17 studies reported that >80% of the patients returned to preinjury activity levels, no assessment of symptoms or functional limitations experienced during or after participation was provided. Only four studies [75, 78–80] determined the effect of operative factors, gender, or psychological factors on return to preinjury sport levels in young athletes (Table 6.8).

Table 6.6 Criteria to return to sport after ACL reconstruction in amateur athletes

Study	Criteria to return to sport
Grindem et al. [21], Nawasreh et al. [22]	DOC: <10% deficit isometric quadriceps strength, limb symmetry four single-leg hop tests; >90% scores KOOS-ADLS, GRS
Failla et al. [27]	DOC: < 10% deficit isometric quadriceps strength, limb symmetry four single-leg hop tests; >90% scores KOOS-ADLS, GRS MOON: <15% deficit 4 single-leg hop tests, ≥ 9 IKDC GRKF, no functional complaints, confidence running, cutting, jumping at full speed
Rosso et al. [34]	<15% deficit isokinetic quadriceps and hamstring strength, <10% deficit single-leg hop, clinical knee stability, no pain or effusion
Lentz et al. [36]	<15% deficit isokinetic quadriceps strength, full ROM, no effusion, completion agility and sport-specific program
Sousa et al. [38]	<15% deficit isokinetic quadriceps and hamstring strength, <10% deficit three single-leg hop tests
Mascarenha et al. [4]	At 6 months if <10% deficit muscle strength, no effusion, full ROM
Noyes and Barber-Westin [48] and Barber-Westin et al. [49]	6–9 months when running program completed and no pain, swelling, giving way, and <3 mm increase anteroposterior tibial translation on knee arthrometer test
Allen et al. [26]	Patient gained functional stability and symmetric lower extremity strength
Ardern et al. [32]	Completion rehabilitation program, full ROM, stable knee, functional quadriceps control, no effusion
Ardern et al. [44]	Completion rehabilitation program, full ROM, stable knee, functional quadriceps control, no effusion
Devgan et al. [41]	Close to full ROM and muscle strength
Almeida et al. [28]	6 months for sports movements, 8 months for contact sports
Salmon et al. [23]	≥ 6 months clinical confirmation ligament stability by surgeon
Bourke et al. [24]	6–9 months when rehabilitation goals met
Criteria not provided	Smith [3], Brophy [25], Takazawa [20], Beischer [29], Laboute [30], Lefevre [31], Hamrin Senorski [35], Hamrin Senorski [46], Novaretti [37], Rodriguez-Roiz [39], Langford [40], Dunn [42], Sandon [43], Faltstrom [45], Nwachukwu [5], Webster [47, 50]

DOC Delaware-Oslo ACL Cohort, *GRKF* Global Rating of Knee Function, *GRS* Global Rating Score, *KOOS-ADLS* Knee Injury and Osteoarthritis Outcome Activities Daily Living score, *IKDC* International Knee Documentation Committee, *MOON* Multicenter Orthopaedic Outcomes Network, *NP* not provided, *ROM* range of motion

Table 6.7 Return to sport after primary ACL reconstruction in children and adolescent athletes

	Cohort					
Study, country	No. of boys, girls	Mean age (range)	Mean follow-up year	Preinjury sports	Criteria to return to sport	RTS % and factors
Salmon et al. [23]	Total 38	16 (14–18)	19.7	NP	≥ 6 months clinical confirmation ligament stability by surgeon	78% at any time; current f.u. 61% strenuous/very strenuous, 26% moderate, 13% light
Takazawa et al. [20]	52, 0	17 (14–19)	4.7	Rugby	NP	90% preinjury at some time, 43% at final f.u.
Dekker et al. [70]	34, 51	13.9 (6–17)	4	Marx; basketball (35%), soccer (28%), football (11%)	NP	84% preinjury level, 7% lower level, 9% no sports
Morgan et al. [76]	138, 104	16 (13–18)	16.6	NP	6–9 months when rehab goals met	69% preinjury
Shelbourne et al. [68]	83, 319	15.6 (12–17)	9.8	Soccer and basketball	< 15% deficit quadriceps strength	87% basketball (boys and girls) 93% soccer girls, 80% soccer boys

Table 6.7 (continued)

Study, country	Cohort No. of boys, girls	Mean age (range)	Mean follow-up year	Preinjury sports	Criteria to return to sport	RTS % and factors
Shelbourne et al. [53]	218, 310	<18	5	92% jumping, twisting, pivoting	NP	92% jumping, twisting, pivoting sports
Schmale et al. [80]	6, 23	14 (NP)	4	Tegner	Tests of strength, coordination, and agility were *not* routinely performed	40% preinjury Positive effect: patient satisfaction score No effect: IKDC ratings
Larson et al. [73]	13, 16	13.9 (9–16)	4	NP	< 10% deficit single-leg hop tests, restoration jump landing and pivoting mechanics	76% preinjury
Graziano et al. [64]	30, 12	12 (10–15)	1	Variety; soccer, lacrosse most common	KT-1000, isokinetic testing, single-leg hop (values NP); qualitative assessment single-leg squat, jump in place, deceleration tasks	93% preinjury
Placella et al. [77]	14, 10	13.1 (9–14)	8	Tegner	Good muscular and articular functional recovery in isokinetic and kinematic tests (data NP)	69% preinjury, 31% lower level
Holwein et al. [78]	28, 14	13.2 (9–15)	2	Tegner, 70% competitive sports	NP	64% preinjury, 19% lower level Positive effect: longer follow-up No effect: IKDC 2000 Subjective Evaluation
Redler et al. [61]	12, 6	14.2 (11–15)	3.6	Tegner mean 8.6	Usually at 6 months	100% preinjury
Calvo et al. [65]	16, 11	13 (12–16)	10.6	Tegner 4–9	<10% deficit isokinetic strength	89% preinjury level, 11% lower level
Edwards et al. [63]	8, 11	13.6 (11–15)	2.8	NP	NP	95% preinjury
Cohen et al. [66]	11, 15	13.3 (11–15)	3.7	NP	NP	89% preinjury level
Dei Giudici et al. [67]	14, 5	13.9 (12–16)	5	Tegner 7–10	NP	89% preinjury, 11% no sports
Kocher et al. [58]	23, 36	14.7 (11–16)	3.6	Variety	Usually at 6 months	100% cutting, pivoting sports
Cassard et al. [59]	20, 8	13 (9–15)	2.8	Tegner 6–9	NP	100% preinjury
Nikolaou et al. [72]	56, 38	13.7 (11–15)	3.2	Tegner 5–9	NP	78% preinjury
Goddard et al. [69]	21, 11	13 (8–16)	2	IKDC	12 months	86% very strenuous, 7% strenuous, 7% moderate
Beischer et al. [29]	21, 30	NP (15–20)	1	Tegner ≥6	NP	74% Tegner ≥6

(continued)

Table 6.7 (continued)

Study, country	Cohort			Preinjury sports	Criteria to return to sport	RTS % and factors
	No. of boys, girls	Mean age (range)	Mean follow-up year			
Chicorelli et al. [75]	142 total	12.7 (6–14)	5.9	NP	NP	75% preinjury or higher (30% higher), 45% (preinjury), 22% lower level Positive effect: younger age No effect: gender, body mass index, cause ACL injury
Aronowitz et al. [71]	19. 10	13.4 (11–15)	2.1	NP	<10% deficit quadriceps strength	84% reinjury, 16% lower level
Hui et al. [60]	12, 4	12 (8–14)	2.1	IKDC	6–9 months when achievement of goals met	100% strenuous activities (0 failure)
Cordasco et al. [62]	17, 6	12.6 (9–14)	2.7	Marx, soccer, skiing, lacrosse	NP	96% unrestricted competitive sports (0 failure)
Webster et al. [74]	82, 58	17.2 (NP)	5	Level I or II Cincinnati Sports Activity Scale	NP	76% preinjury at any time; 51% preinjury at latest f.u., 34% lower level, 15% no sports. Inclusionary criteria: no reinjuries or graft failures
McCullough et al. [79]	68, 0	NP (14–18)	2	Football	NP	45% preinjury level, 26% lower level of performance, 28% did not return No effect: concurrent operative procedures or articular injuries, MCL tears Negative effect: other interests, physical symptoms, advice, fear reinjury

IKDC International Knee Documentation Committee, *MCL* medial collateral ligament, *NCAA* National Collegiate Athletic Association, *NP* not provided, *RTS* return to sport

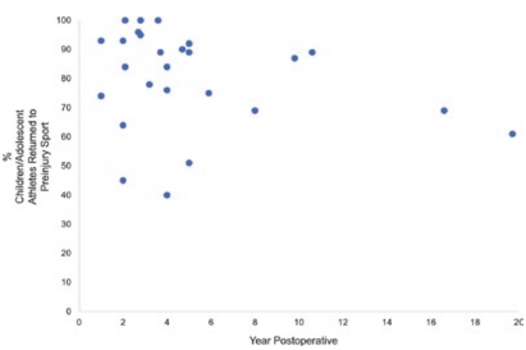


Fig. 6.4 Data from 27 studies that followed 2307 children/adolescent athletes are shown regarding the percent who returned to preinjury sports activities after ACL reconstruction

6.3.2 Reinjuries: Rates and Significant Factors

Reinjury rates in 10,453 children and adolescent athletes are shown in Table 6.9. Large cohort investigations from Fauno et al. [81] ($N = 3215$) and Webster et al. [54] ($N = 110$) provided only reinjury rates; RTS percentages were not determined. Average injury rates were 9% (range, 0–38%) for the ACL graft (Fig. 6.5), 16% (range, 5–42%) for the contralateral ACL, and 29% (range, 12–51%) for either ACL (Fig. 6.6). Factors associated with reinjuries are summarized in Table 6.10. Similar to the findings from

Table 6.8 Summary of factors affecting return to sport after ACL reconstruction in children and adolescent athletes

Factor	Effect on RTS (no. studies) Positive	Negative	None	Total no. of studies
Age	1 ("younger")			1
Gender			1	1
Preoperative body mass index			1	1
Mechanism of injury			1	1
Surgical				
Associated cartilage injury			1	1
Associated medial collateral ligament injury			1	1
Postoperative symptoms		1		1
Longer follow-up	1			1
Patient satisfaction scores	1			1
Fear reinjury		1		1
Advice to stop sports		1		1
Other interests		1		1
IKDC Subjective Knee Evaluation form			2	2

IKDC International Knee Documentation Committee

Table 6.9 Reinjury/failure rates upon return to sport after ACL reconstruction in children and adolescents

Study	Mean follow-up year	Primary ACL reconstruction graft (no.)[a]	Reinjury/failure rate: ACL-R knee[b]	ACL-C knee	Either knee	Sports comments[b]	Other factors associated with reinjuries/failures[b]: ACL-reconstructed knee	Contralateral knee
Salmon et al. [23]	20	Hamstring (39)	38%	13%	51%	Nearly all reinjuries to either knee associated with sports	Compared with adults: male (HR 4.8, $P = 0.001$), female (HR 2.6, $P < 0.05$), PTS ≥ 12° (HR 11.1, $P = 0.001$)	Posterior tibial slope ≥ 12° (HR 7.3, $P = 0.004$)
Takazawa et al. [20]	4.7	Hamstring and Telos artificial ligament (52)	23%	10%	33%	All patients rugby players, all reinjuries during rugby	Compared with adults: age <20 years ($P = 0.006$)	None
Dekker et al. [70]	4	Hamstring, BPTB, hamstring, and allograft (85)	20%	14%	34%	All participated in sports, reinjuries during sports	None	None
Morgan et al. [76]	16.6	Hamstring (194)	20%	17.5%	28%	Contralateral knee reinjuries associated with cutting, pivoting sports (HR 2.3, $P = 0.05$)	Family history ACL injury (HR 3.6, $P = 0.001$)	Male gender (HR 2.1, $P < 0.05$), return IKDC level 5 cutting, pivoting sport (HR 2.3, $P = 0.05$)
		BPTB (48)	8%	29%	37%			
		Total (242)	17%	20%	37%			
Shelbourne et al. [68]	9.8	BPTB (402)	10%	16%	23%	All reinjured during sports	None	None

(continued)

Table 6.9 (continued)

Study	Mean follow-up year	Primary ACL reconstruction graft (no.)[a]	Reinjury/failure rate			Sports comments[b]	Other factors associated with reinjuries/failures[b]	
			ACL-R knee[b]	ACL-C knee	Either knee		ACL-reconstructed knee	Contralateral knee
Shelbourne et al. [53]	5	Males (218)	10%	5%	15%	Reinjuries to either knee associated with basketball or soccer	Compared with adults: age <18 years ($P < 0.0001$)	Compared with adults: age <18 years ($P < 0.0001$); female gender age <18 years ($P < 0.01$)
		Females (310)	7%	12%	19%			
Schmale et al. [80]	4	Hamstring or tibialis anterior allograft (29)	14%	28%	41%	NP	NP	NP
Larson et al. [73]	4	Hamstring (22) Tibialis anterior allograft (8)	17%	17%	33%	All reinjuries during sports	None	None
Graziano et al. [64]	1	Hamstring (42)	12%	5%	17%	All reinjuries noncontact	None	None
Placella et al. [77]	8	Hamstring (24)	0%	42%	42%	All skeletally immature athletes at ACL surgery	None	None
Holwein et al. [78]	2	Hamstring (42)	7%	5%	12%	All reinjured during sports	None	None
Redler et al. [61]	3.6	Hamstring (18)	0%	17%	17%	All reinjured during sports	None	None
Calvo et al. [65]	10.6	Hamstring (27)	11%	NP	NP	3/4 reinjuries during contact sports	None	None
Edwards et al. [63]	2.8	Hamstring (15), BPTB (5)	20%	NP	NP	2/4 reinjuries during sports	None	None
Cohen et al. [66]	3.7	Hamstring (26)	11.5%	NP	NP	All traumatic reinjuries	None	None
Dei Giudici et al. [67]	5	Hamstring (19)	10.5%	NP	NP	All traumatic reinjuries	None	None
Kocher et al. [58]	3.6	Hamstring (61)	3%	NP	NP	All reinjured during sports	None	None
Cassard et al. [59]	2.8	Hamstring (28)	7%	NP	NP	1/2 reinjured during sports	None	None
Nikolaou et al. [72]	3.2	Hamstring (94)	4%	NP	NP	All traumatic reinjuries	None	None
Goddard et al. [69]	2	Hamstring (32)	6%	NP	NP	1/2 reinjured during sports	None	None
Beischer et al. [29]	1	NP	0%	NP	NP	NA	NA	NA
Chicorelli et al. [75]	12.7	Variety of grafts	0%	NP	NP	NA	NA	NA
Aronowitz et al. [71]	1.2	Achilles tendon allograft (19)	0%	NP	NP	NA	NA	NA

Table 6.9 (continued)

Study	Mean follow-up year	Primary ACL reconstruction graft (no.)[a]	Reinjury/failure rate			Sports comments[b]	Other factors associated with reinjuries/failures[b]	
			ACL-R knee[b]	ACL-C knee	Either knee		ACL-reconstructed knee	Contralateral knee
Hui et al. [60]	2.1	Allograft (15), hamstring (1)	0%	NP	NP	NA	NA	NA
Cordasco et al. [62]	2.7	Hamstring (23)	0%	NP	NP	NA	NA	NA
Webster et al. [54]	4.8	Hamstring (110)	14%	15%	29%	NP	Compared with adults (OR 6.3, $P = 0.0001$)	Compared with adults (OR 3.1, $P = 0.001$)
Ellis et al. [130]	2	BPTB (59)	3%	NP	NP	78% reinjured during sports	Use of allograft 15× more likely to fail ($P = 0.001$)	NA
		BPTB allograft (20)	35%					
Fauno et al. [81]	5	Hamstring or BPTB (3215)	5%	NP	NP	NP	59% age 13–14 and 48% age 15–19 reinjuries due to sports trauma	None
Andernord et al. [56]	2	Hamstring, BPTB (4950)	3.5%	NP	NP	Soccer players rate revision: males 4.3% (RR 2.87, $P < 0.001$), females 4.6% (RR 2.59, $P < 0.001$)	Compared with adults: age <20 males RR 2.67 ($P < 0.001$), females RR 2.25 ($P < 0.001$)	NA

ACL anterior cruciate ligament, *ACL-R* anterior cruciate ligament reconstruction, *ACL-C* anterior cruciate ligament contralateral, *BPTB* bone-patellar tendon-bone, *HR* hazard ratio, *IKDC* International Knee Documentations Committee, *KOOS-QOL* Knee Injury and Osteoarthritis Outcome-Quality of Life, *NA* not assessed, *NP* not provided, *OR* odds ratio, *RR* relative risk, *STG* semitendinosus-gracilis

[a]Autograft unless otherwise indicated

[b]Statistical values given when provided in study

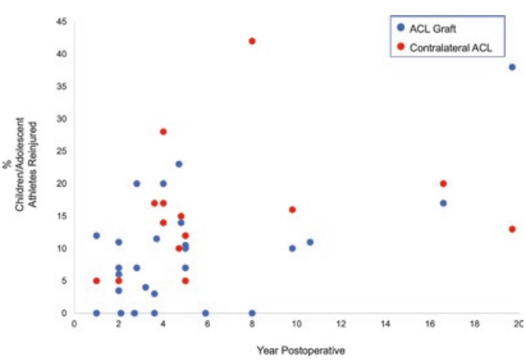


Fig. 6.5 Percentages of postoperative ACL injuries in children and adolescent athletes are shown. There was a significant association between ACL graft reinjury rates and time postoperatively ($R^2 = 0.31$, $P < 0.01$)

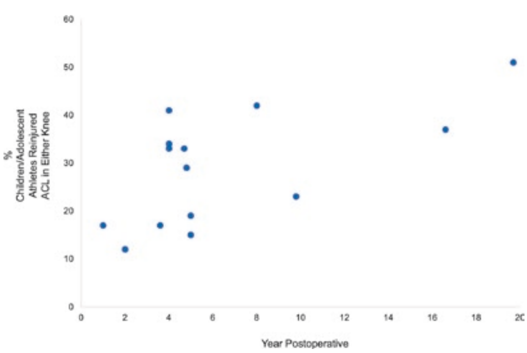


Fig. 6.6 Percentages of postoperative ACL injuries in either knee in children and adolescent athletes are shown ($R^2 = 0.40$, $P = 0.01$)

Table 6.10 Summary of factors statistically associated with reinjury/failure rates after ACL reconstruction in children and adolescent athletes

Factor	ACL graft No. of studies	Contralateral ACL No. of studies
Return cutting, pivoting sports	4	5
Family history ACL tear	2	1
Age <20 (compared with adult)	2	1
Age <18 (compared with adult)	1	2
Age ≤20 and male gender	1	0
Age ≤20 and female gender	1	0
Contact injury	1	0
Posterior tibial slope ≥12° and age ≤18	1	1
Use of allograft	1	0
Male gender (compared with adult)	1	1
Female gender (compared with adult)	1	0
Age ≤18 and female gender	0	1

amateur athlete studies, return to sport involving cutting and pivoting was the most common factor related to reinjury of either the ACL graft or the contralateral ACL.

6.3.3 Published Criteria for Release to Unrestricted Activities

Few RTS criteria were described in the studies that focused on children and adolescent athletes (Table 6.11). Fourteen of these studies failed to provide any RTS criteria and two provided only time postoperative. Although four studies mentioned objective tests that had to be passed, the specific RTS goals of these tests were not given.

6.3.4 Conclusions and Recommendations

Observations of RTS rates in children and adolescent athlete studies show mostly positive results, with the majority of studies (19 of 27) reporting ≥75% of athletes returning to preinjury activity levels. The question of whether high activity levels are maintained remains unanswered; four of five long-term studies assessed in this chapter found a drop-off in the RTS rate of 61–69% (8–20 years postoperatively). Importantly, the RTS data is offset by high reinjury rates. In the 14 studies that provided injury rates to both knees, an average of 29% of these athletes sustained either a rupture to the ACL graft or to the contralateral ACL. We speculate that high reinjury rates in young athletes are due to a multitude of factors, with the failure to adequately assess if normal muscular and neuromuscular indices have been achieved before RTS being one of particular

Table 6.11 Criteria to return to sport after ACL reconstruction in children and adolescent athletes

Study	Criteria to return to sport
Calvo et al. [65]	<10% deficit isokinetic strength
Aronowitz et al. [71]	<10% deficit quadriceps strength
Larson et al. [73]	<10% deficit single-leg hop tests, restoration jump landing and pivoting mechanics
Shelbourne et al. [68]	<15% deficit quadriceps strength
Placella et al. [77]	"Good" muscular and articular functional recovery in isokinetic and kinematic tests (values NP)
Graziano et al. [64]	KT-1000, isokinetic testing, single-leg hop (values NP); qualitative assessment single-leg squat, jump in place, deceleration tasks
Kocher et al. [58], Redler et al. [61]	Usually at 6 months
Goddard et al. [69]	12 months
Hui et al. [60]	6–9 months when achievement of goals met
Morgan et al. [76]	6–9 months when rehabilitation goals met
Criteria not provided	Cassard [59], Cordasco [62], Takazawa [20], Cohen [66], Dei Giudici [67], Dekker [70], Nikolaou [72], Webster [74], Chicorelli [75], Beischer [29], Holwein [78], McCullough [79], Schmale [80][a], Edwards [63]

NP not provided
[a]Schmale [80] – Authors stated tests of strength, coordination, and agility were *not* routinely performed

concerns. Clinicians should insist on the completion of advanced neuromuscular retraining (Sportsmetrics, Chap. 14) in athletes under the age of 20 who desire to return to high-risk sports. Multiple objective tests should be conducted as previously described for amateur athletes to advance the young patient through end-stage rehabilitation and before release to unrestricted activities.

6.4 Elite Collegiate and Professional Athletes

6.4.1 Return to Sport: Rates and Influential Factors

Few studies have determined RTS rates after ACL reconstruction in collegiate athletes [79, 82–84] (Table 6.12) or examined the factors that

Table 6.12 Return to sport after primary ACL reconstruction in elite collegiate and professional athletes

Study	Preinjury sport	Return to sport percentages	Return to sport factors
Kamath et al. [82]	NCAA Division I all sports ($n = 42$ males, 47 females)	88% returned ≥1 year, 67–87% remaining eligibility used	No effect: concurrent meniscal or chondral injuries
Howard et al. [83]	NCAA Division I soccer ($n = 78$ females)	85% returned ≥1 year, 73% played for remaining collegiate eligibility	Positive effect: scholarship recipient, remaining years eligibility No effect: player position, depth chart status, use of knee injury prevention program, mean time return to practice or games, graft type, graft fixation, previous ACL reconstruction, concomitant operative procedures
Daruwalla et al. [84]	NCAA Division I football ($n = 184$)	82% returned; starting players 94%, utility players 88%, rarely played 73%	Positive effect: autograft, scholarship recipient No effect: concomitant operative procedures, graft fixation
McCullough et al. [79]	NCAA Football (division NP) ($n = 26$)	38% returned same level, 29% returned lower level of performance, 33% did not return	Negative effect: fear reinjury, other interests, symptoms, advice No effect: concurrent operative procedures or articular injuries
Mai et al. [85]	NFL ($n = 205$), NBA ($n = 76$), NHL ($n = 48$), MLB ($n = 21$)	NHL 96%, NBA 85%, NFL 82%, MLB 81%	NP
Cinque et al. [86]	NFL, lineman ($n = 72$)	62% offensive lineman, 66% defensive linemen returned NFL. No difference performance compared with controls	NP
Read et al. [87]	NFL, defensive players ($n = 38$)	74% returned for at least 1 game, 61% returned for at least half a season, 26% remained active 3 seasons after surgery. Significant poorer difference performance compared with controls	Positive effect: lower BMI, better performance before injury No effect: age, height, position
Erickson et al. [88]	NFL quarterbacks ($n = 13$)	92% returned, career length mean 4.8 ± 2.7 seasons. No significant differences control performance	NP
Carey et al. [89]	NFL running backs and wide receivers (33)	79% returned, decrease in performance	NP

(continued)

Table 6.12 (continued)

Study	Preinjury sport	Return to sport percentages	Return to sport factors
Yang et al. [90]	NFL, all positions (*n* = 154)	56% returned <18 months, 62% returned >18 months	Positive effect: early round draft pick, late-round draft pick of unskilled players No effect: skilled position
Eisenstein et al. [91]	NFL, all positions (*n* = 92)	62% returned NFL	Positive effect: In-season injury, early round draft pick No effect: offensive, defensive, or special teams play; time of game, time of season; playing surface, concomitant injury, previous ACL reconstruction, contact vs. noncontact injury
Shah et al. [92]	NFL, all positions (*n* = 49)	63% returned	Positive effect: no. of games before surgery, greater career length, early round draft pick No effect: age, position, concurrent procedures
Harris et al. [93]	NBA (*n* = 58)	98% returned the season following surgery. Career length 4.3 ± 3.4 years. Performance declined but not significantly different compared with controls	NP
Kester et al. [94]	NBA (*n* = 79)	86% returned, career length mean 4.6 ± 2.8 seasons. Significantly different compared with control career length, games played, player efficiency rating, minutes played per game	NP
Busfield et al. [95]	NBA (*n* = 27)	78% returned, career length mean four seasons. Performance rating declined compared with control group	Positive effect: no concurrent procedures
Erickson et al. [96]	MLS (*n* = 52)	77% returned	NP
Walden et al. [97]	Professional men's soccer in Sweden (*n* = 91)	64% playing same level, 23% lower level, 13% not playing	NP
Zaffagnini et al. [98]	Professional men's soccer in Italy (*n* = 21)	62% playing same level, 9% lower level	NP
Fabricant et al. [99]	MLB (*n* = 26)	88% returned. Decline in number of games played	NP
Erickson et al. [100]	NHL (*n* = 36)	97% returned NHL, 3% other hockey league. NHL career length mean 4.4 ± 3.3 years, performance not different from preinjury	None
Kyritsis et al. [101]	Professional men's clubs in Qatar (*n* = 158)	100%	NP
Namdari et al. [103]	WNBA (*n* = 18)	78% returned WNBA, the seasons following surgery. Performance declined but not significantly different compared with controls	No effect: age, BMI

BMI body mass index, *MLB* Major League Baseball, *NBA* National Basketball Association, *NCAA* National Collegiate Athletic Association, *NFL* National Football League, *NHL* National Hockey League, *NP* not provided influenced RTS (Table 6.13). Kamath et al. [82] identified National Collegiate Athletic Association (NCAA) Division I athletes from one university who had undergone ACL reconstruction either before entering college (35 athletes) or while attending college (54 athletes). All athletes participated in at least one NCAA sport including soccer, lacrosse, football, and basketball. The athletes who underwent surgery before college were on the varsity roster of their team for an average of 3.1 years and used 78% of their predicated 4 years of eligibility. Eighty-eight percent of the athletes who had ACL reconstruction while in college played for at least one season and used from 67% to 87% of their remaining eligibility. Factors that may have influenced RTS rates were not assessed in this study.

Howard et al. [83] determined RTS rates in 78 female soccer players from 14 NCAA teams who sustained ACL injuries during collegiate competition. Twenty-four athletes had a history of a prior ACL reconstruction (on either knee). Overall, 85% RTS after ACL reconstruction, with 73% playing through their remaining college eligibility and 75% returning to the same or a higher position on the depth chart (starter, utility player, or rarely used player). RTS was not influenced by player position, depth chart status, use of a knee injury prevention program, type of ACL graft,

Table 6.13 Summary of factors affecting return to sport after ACL reconstruction in elite collegiate and professional athletes

Factor	Effect on RTS (no. of studies)			Total no. of studies
	Positive	Negative	None	
Collegiate scholarship recipient	2			2
Collegiate remaining years of eligibility	1			1
Player position			5	5
Depth chart status			1	1
Use of knee injury prevention program			1	1
Early round draft pick	3			3
Late round draft pick unskilled players	1			1
In-season injury	1		1	2
Time of game			1	1
Playing surface			1	1
Greater number of games played before surgery	1			1
Longer career length	1			1
Time to return to practice or games			1	1
Mechanism injury			1	1
Previous ACL reconstruction			2	2
Age			3	3
Height			1	1
Body mass index	1 (“lower”)		1	2
Mechanism of injury			1	1
Surgical				
ACL autograft type			1	1
ACL autograft vs. allograft	1			1
ACL graft fixation method			2	2
Associated cartilage injury			2	2
Associated meniscal injury			2	2
Any concomitant procedure	1 (none)		4	4
Postoperative symptoms		1		1
Higher-performance level preinjury	1			1
Fear reinjury		1		1
Advice to stop sports		1		1
Other interests		1		1

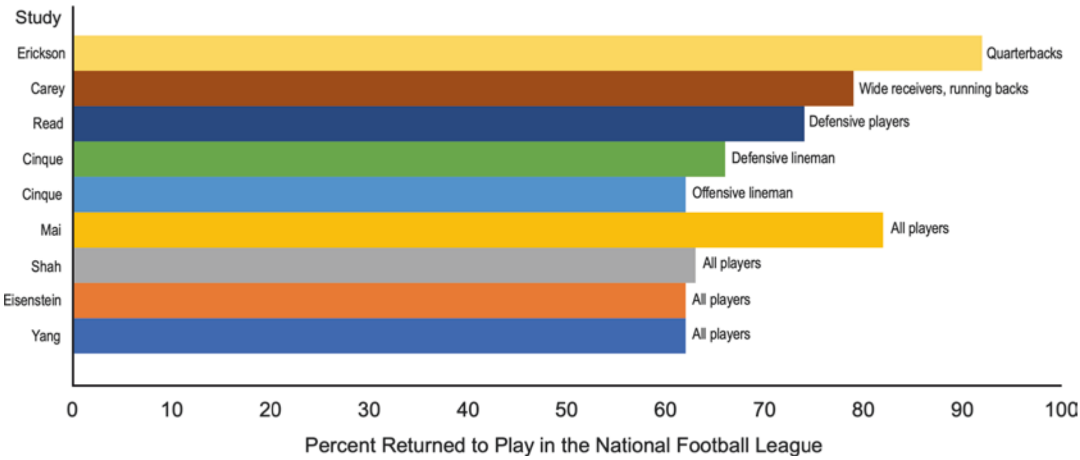


Fig. 6.7 Percentages of National Football League players who returned to league competition after ACL reconstruction

graft fixation techniques, or concomitant meniscus procedure.

Two studies focused on NCAA football players who underwent ACL reconstruction for injuries sustained during collegiate play. Daruwalla et al. [84] followed 184 Division I players and reported 82% RTS. Starting players returned at a 94% rate; utility players, at an 88% rate; and players rarely used, at a 73% rate ($P = 0.004$). Players on an athletic scholarship had a higher RTS rate than those not on a scholarship (88% and 69%, respectively; $P = 0.008$). Players who received an autograft had a higher RTS rate than those who received an allograft (84% and 69%, respectively; $P < 0.05$). There was no effect on RTS rates from concomitant operative procedures or type of graft fixation. McCullough et al. [79] identified 26 collegiate football players who underwent ACL reconstruction from the MOON cohort, of whom 38% returned to football at the same performance level and 29% returned at a lower level of performance. Of those who did not return to football, 50% cited fear of reinjury, 25% advise, 12% physical symptoms, and 12% loss of speed or strength as primary reasons.

RTS rates following ACL reconstruction in professional athletes were reported in 18 studies [85–102] for 1508 male athletes and in 1 study [103] for 18 female athletes. Nine studies reported data on 657 players from the National Football League (NFL, Fig. 6.7). Four studies reported RTS for any position ranged from 62% to 82% [85, 90–92]. A positive influence for RTS was found on early round draft pick players, whereas specific player position and concurrent operative procedures had no effect. A study of NFL defensive players found that 74% returned for at least one game and 61% returned for at least half of a season [87]. However, the players' performance was poorer compared with controls and only 26% were still actively playing three seasons after surgery. In a study on NFL lineman, 62% of offensive and 66% of defensive players returned to football, with no difference in performance compared with controls [86].

Four investigations of National Basketball Association (NBA) players found RTS rates ranging from 78% to 98% (Fig. 6.8) [85, 93–95]. A high rate of RTS was found in two studies on National Hockey League players of 96% [85] and 97% [100].

Two studies reported post-ACL reconstruction RTS rates equivalent of preinjury status in professional soccer players in Sweden [97] and Italy [98] of 64% and 62%, respectively (Fig. 6.9). In the USA, data on 52 male Major League Soccer players who underwent ACL reconstruction was evaluated [96]. Seventy-seven percent returned play the following season and their mean career

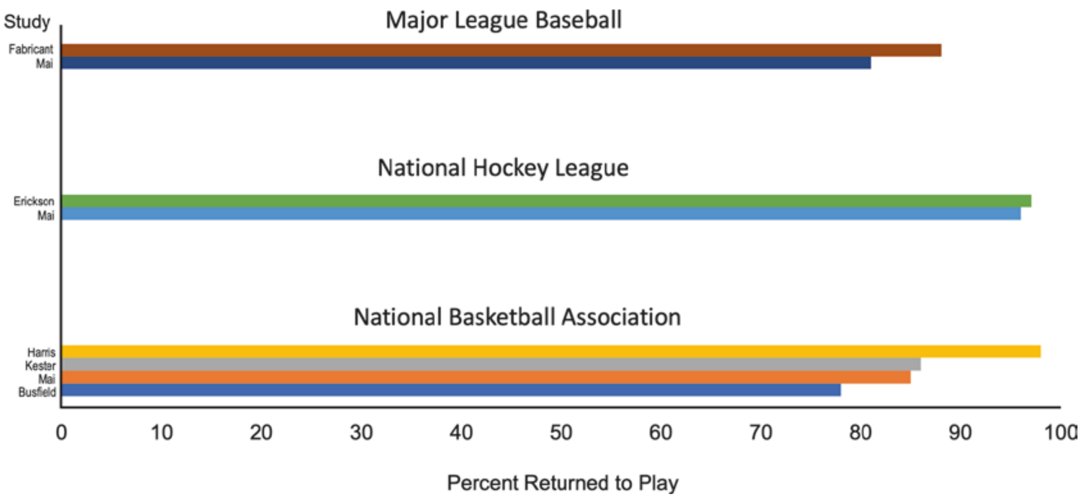


Fig. 6.8 Percentages of professional athletes who returned to play in their respective league after ACL reconstruction

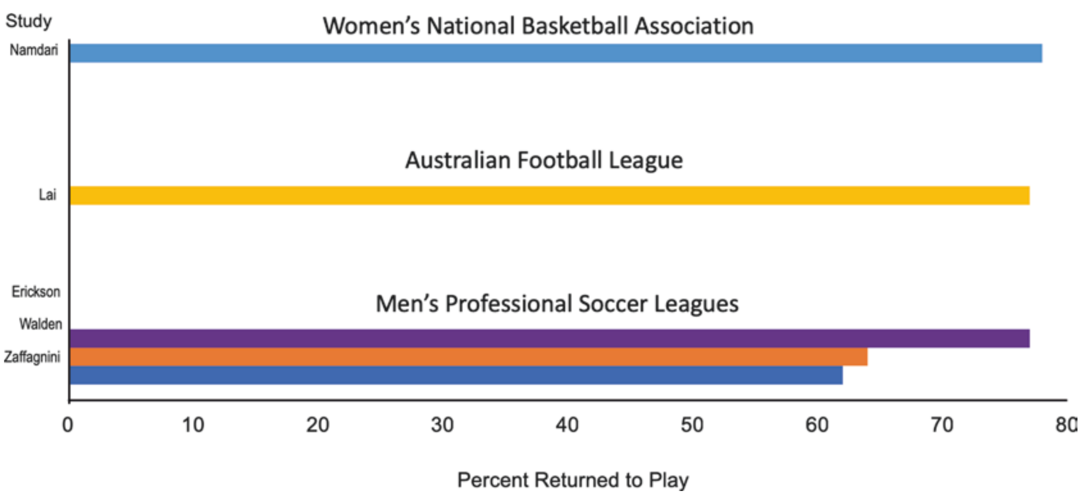


Fig. 6.9 Percentages of professional athletes who returned to play in their respective league after ACL reconstruction

length was 4.0 ± 2.8 years. Player performance was not significantly different compared with preinjury. One investigation reported that 77% of 158 players in the Australian Football League returned to at least 1 match after ACL reconstruction [102]. Factors significantly associated with RTS were experience (played in >50 matches before ACL injury, $P < 0.001$) and high draft pick ($P = 0.003$).

To date, only one study has focused on women professional athletes [103]. Eighteen players from the Women's National Basketball Association (mean age, 26.8) underwent ACL reconstruction and 78% RTS the following season. Although performance indices declined, they were not significantly different from controls.

6.4.2 Reinjuries: Rates and Significant Factors

Few studies investigated reinjury rates in collegiate and professional athletes (Table 6.14). Kamath et al. [82] reported that NCAA athletes who underwent ACL reconstruction before enter-

Table 6.14 Reinjury/failure rates upon return to sport after ACL reconstruction in elite collegiate and professional athletes

Study	Demographics			Reinjury/failure rate	
	Sport	Years of study	No. of athletes	ACL graft	Contralateral ACL
Kamath et al. [82]	NCAA division I all sports	2000–2009	89 Precollegiate ACL recon (35), intracollegiate ACL recon (54)	Precollegiate: 17% Intercollegiate: 2%	Precollegiate: 20% Intercollegiate: 11%
Kyritsis et al. [101]	Pro sports clubs	2008–2015	All patients 158	16.5%	7%
			Fully discharged[a] 116	10%	NP
			Not fully discharged 42	33%	NP
Mai et al. [85]	Major League Baseball	1984–2013	21	14%	0%
Mai et al. [85]	National Football League	1984–2013	205	3%	3%
Mai et al. [85]	National Hockey League	1984–2013	48	1%	0%
Erickson et al. [100]	National Hockey League	1990–2013	36	2.5%	NP
Harris et al. [93]	National Basketball Association	1975–2012	58	3%	NP
Kester et al. [94]	National Basketball Association	1984–2014	79	1%	NP
Mai et al. [85]	National Basketball Association	1984–2013	76	1%	1%
Namdari et al. [103]	Women's National Basketball Association	1998–2008	18	5%	NP
Zaffagnini et al. [98]	Pro soccer	2009	21	5%	NP
Walden et al. [97]	Pro soccer	2001–2015	91	5%	NP
Lai et al. [102]	Australian Football League	1999–2013	158	30% either knee	30% either knee

NCAA National Collegiate Athletic Association, *NP* not provided
[a]See Table 6.16

ing college had an ACL graft reinjury rate of 17% and a contralateral ACL injury rate of 20%; the combined reinjury rate (to either knee) was 37%. Athletes who had ACL reconstruction while in college had an ACL graft reinjury rate of 2% and a contralateral ACL injury rate of 11%; the combined reinjury rate was 13%. The authors concluded that elite-level adolescent athletes who undergo ACL reconstruction while in high school have high rates of reinjury, which is consistent with our analysis of this subgroup.

Gans et al. [1] described the epidemiology of recurrent ACL injuries (after ACL reconstruction) in NCAA sports tracked between 2004 and 2014 (Table 6.15). Rates of reinjuries were calculated per 10,000 athlete exposures. The authors identified 126 athletes with ACL reinjuries (from 350,416 athlete exposures). The highest rates were among male football players (15), female gymnasts (8.2), and female soccer players (5.2).

Kyritsis et al. [101] followed 158 male professional athletes who returned to their previous level to determine the effect of not meeting discharge criteria on reinjury rates. All players underwent a series of tests, with discharge criteria consisting of completion of on-field sports-specific rehabilitation, <10% quadriceps deficit on isokinetic testing (60°/s), <11 s to complete a running *t*-test, and <10% deficit in limb symmetry on a single hop, a single-leg triple hop, and a

Table 6.15 Epidemiology of recurrent ACL injuries in National Collegiate Athletic Association sports Injury Surveillance Program, 2004–2014 [1]

Sport	Recurrent ACL tear rate per 10,000 athlete exposures (95% CI)	Rate ratios between genders
Soccer		
Women	5.2 (3.2–7.9)	3.8 (1.3–15), $P = 0.02$
Men	1.4 (0.4–3.3)	
Basketball		
Women	2.6 (1.6–4.1)	1.9 (0.8–4.3), P = NS
Men	1.4 (0.7–2.6)	
Lacrosse		
Women	3.6 (1.3–8.1)	1.4 (0.3–5.8), P = NS
Men	2.6 (0.7–7.1)	
Ice hockey		
Men	0.9 (0.1–3.2)	0.0 (0–8.6), P = NS
Women	0	
Football (men)	15 (11–19)	NA
Gymnastics (women)	8.2 (3.3–17)	NA
Field hockey (women)	4.1 (1.3–9.9)	NA
Volleyball (women)	0.9 (0.3–2.2)	NA

NA not applicable, *NS* not significant

single-leg triple crossover hop. Overall, 16.5% sustained an ACL graft rupture and 7% sustained a contralateral ACL tear. Not meeting all discharge criteria significantly increased the risk of reinjury (HR 4.1, $P < 0.001$). Of the 26 athletes who sustained a graft rupture, 65% did so within the first 6 months after RTS. Other studies that reported reinjury rates in professional athletes typically reported lower rates of ACL graft injuries and only one reported rates of contralateral ACL ruptures. Mai et al. [85] retrospectively determined ACL graft and contralateral ACL injury rates in four professional sports leagues in the USA. The ACL graft reinjury percentage for Major League Baseball (14%) appears somewhat inflated because only 21 players were included in this group, of whom 3 were reinjured.

Lai et al. [102] reported an overall reinjury rate of 30% for ACL injuries to either knee in Australian football players. Factors significantly associated with reinjury rates were experience (played in ≤50 matches, $P = 0.04$) and age under 21 years ($P = 0.001$).

Table 6.16 Criteria to return to sport after ACL reconstruction in collegiate and professional athletes

Study	Criteria to return to sport
Kyritsis et al. [101]	<10% deficit isokinetic quadriceps strength, <10% deficit 3 single-leg hop tests, <11 s running *t*-test, on-field sports-specific rehabilitation completed
Zaffagnini et al. [98]	"On-field rehabilitation" begun: <20% deficit isokinetic strength, no laxity or giving way, minimal pain and effusion, full ROM Criteria for full release to soccer not provided
Criteria not provided	Collegiate athletes: Daruwalls [84], Howard [83], Kamath [82], McCullough [79] Professional athletes: Harris [93], Namdari [103], Mai [85], Walden [97], Kester [94], Fabircant [99], Busfield [95], Kester [94], Erickson [88], Carey [89], Erickson [100], Lai [102]

ROM range of motion

6.4.3 Published Criteria for Release to Unrestricted Activities

No study in collegiate athletes provided criteria for release to full sports because the investigations were all retrospective. In the professional athlete literature, only Kyritsis et al. [101] provided criteria for RTS (Table 6.16), described previously. Zaffagnini et al. [98] described measures required for athletes to begin on-field rehabilitation of <20% deficit in isokinetic strength, no laxity or giving way, minimal pain and effusion, and full range of motion. Criteria for release to unrestricted sports was not provided.

6.4.4 Conclusions and Recommendations

Few data are available for collegiate athletes who have undergone ACL reconstruction regarding RTS and even less information has been published regarding the risk of reinjury upon return to athletics. Only one comprehensive epidemiological study has appeared to date and this showed high rates of recurrent ACL ruptures among male football players, female gymnasts, and female soccer players. The greatest limitation of this type of study is the lack of information regarding the grafts selected for surgery and details regarding rehabilitation, including the use of objective testing prior to release to unrestricted activities. RTS rates in professional athletes range tremendously, with lower rates usually reported in NFL and professional soccer players compared with other sports. Reinjury rates were only provided in eight studies and were typically ≤5%, with the exception of the study from Kyritsis et al. [101]. Prospective longitudinal studies in collegiate and professional athletes are required to gain further insight into the issue of RTS, impacts on performance and career longevity, and reinjuries.

6.5 Future Concerns

Little is known regarding the effects of RTS after ACL reconstruction on articular cartilage deterioration. To our knowledge, no postoperative longitudinal studies have been conducted using modern magnetic resonance imaging (MRI) techniques to determine whether early return to high-impact activities such as running, jumping, cutting, and pivoting may cause (or progress) cartilage deterioration. Part of the difficulty in ascertaining the potential deleterious effects of RTS is the fact that many factors may cause eventual osteoarthritis (OA) in the ACL-reconstructed knee such as meniscectomy, severe bone bruising and marrow lesions, chondral fractures, damage to other knee ligaments, excessive uncorrected varus or valgus lower limb malalignment, long-term biochemical alternations in the knee joint, obesity, genetics, and long-term abnormal knee kinematics [104–113]. A prospective study design would need to include baseline (preoperative) MRI to rule out several of these factors and would also need to sort patients who undergo isolated ACL reconstruction from those who undergo meniscectomy or other associated procedures or in whom articular cartilage damage exists.

One study that longitudinally followed patients with acute ACL ruptures for several years demonstrated a strong potential for articular cartilage deterioration. Potter et al. prospectively followed 40 patients who underwent baseline MRI within 8 weeks of the injury and again 7–11 years later [112]. The MRI evaluation used a cartilage-sensitive, pulse sequence evaluation with T2 techniques which have shown increased ability to detect traumatic chondral injuries. None of the patients had concurrent damage to the menisci or other knee ligaments or an articular cartilage lesion rated as Outerbridge grade 3 or higher. ACL reconstruction was performed in 28 patients, while no surgery was done in 14. At baseline, all knees had an MRI-detectable cartilage injury, most severely over the lateral tibial plateau. Regardless of surgical intervention, by 7–11 years after injury, the risk of cartilage damage as viewed on MRI for the lateral femoral condyle was 50 times that of baseline, 30 times that for the patella, and 18 times for the medial femoral condyle. The authors did not determine the patients' sports activity levels or when athletics were resumed after surgery, so no conclusion could be drawn from this study regarding the potential effect of RTS on cartilage deterioration.

Van Ginckel et al. [114] compared articular cartilage status in 15 patients treated 6 months earlier with isolated ACL reconstruction with that of matched controls using 3 T MRI with T2 mapping and three-dimensional volume and thickness quantitative assessment. Eight patients returned to sports by 6 months postoperatively, all but one at a decreased level in low-impact activities. Positive correlations were found between accelerated time to RTS and increased cartilage thickness in the medial and lateral tibiofemoral joint and deformation in the lateral femoral condyle. Patients who underwent acute reconstruction (≤ 10 weeks of injury) had delayed cartilage recovery in both tibiofemoral compartments. The authors concluded that the ultrastructural MRI changes suggested early degeneration, corresponding with declining in vivo tissue resiliency which could be potentially harmful with regard to early RTS and high-impact loading.

Van Ginckel et al. [115] conducted a systematic review of 12 longitudinal MRI studies to determine changes in cartilage status over time after ACL reconstruction and factors that could affect the rate of change. The studies varied widely with regard to MRI acquisition and processing. Even so, the authors concluded that progressive macroscopic changes were detectable after 2 years of follow-up and were found in all three compartments (medial and lateral tibiofemoral and patellofemoral). These changes were hypothesized to have been a result of either blunt trauma, changes in the biochemical environment in the knee, coexisting injuries, and/or persistent biomechanical alterations after surgery. Moderate to strong evidence was provided for the following factors regarding increased rate of cartilage change: meniscal lesions or meniscectomy, longer time from injury, presence of baseline bone marrow lesions, and continued altered biomechanics.

The high failure rates reported in many studies in this chapter are especially concerning because ACL revision reconstruction is commonly required in athletes (see Chap. 25). The outcome of revision procedures is usually less desirable than primary ACL reconstruction because of higher subsequent failure rates, increased symptoms and functional limitations, and eventual knee OA [116–119]. One common problem is that patients wait too long to undergo the revision and suffer repeat injuries resulting in meniscectomy and joint arthritis, similar to those reported in ACL natural history studies. Our studies [120–122] have shown that over 90% of knees requiring ACL revision reconstructions have compounding problems such as prior meniscectomy, articular cartilage damage, loss of secondary ligament restraints, varus malalignment, and other ligament damages. These problems led to results that were generally less favorable than those reported following primary ACL reconstruction [119].

Another concern with the high reinjury rates reported by so many investigations is the strong potential for meniscal damage. Additional meniscal surgery was required in 15 of 28 patients (54%) in an ACL revision cohort reported by Ahmed et al. [123]. Brophy et al. [117] noted disruption of the medial meniscus in 35% and 16% of the lateral meniscus of 246 patients at the time of ACL revision reconstruction. Another study involving 1205 patients that underwent ACL revision reported that 45% had medial meniscal pathology and 37% had lateral meniscal tears at the time of surgery [116]. Studies have shown that, regardless of the outcome of ACL reconstruction in terms of restoration of knee stability, meniscectomy accelerates degenerative joint changes [107, 108, 124–129]. Nearly every long-term study has reported a statistically significant correlation between meniscectomy performed either concurrently or after the ACL reconstruction and moderate-to-severe radiographic evidence of OA. Claes et al. [106] systematically reviewed 16 long-term ACL reconstruction studies (follow-up range, 10–24.5 years) involving 1554 subjects. The prevalence of OA was 16.4% in patients with isolated ACL injuries and 50.4% in patients with concurrent meniscectomy (odds ratio [OR] 3.54). Therefore, patients with failed ACL reconstructions who have previously undergone meniscectomy are at an even higher risk for the development of symptomatic knee OA than those with intact menisci.

The prevention of ACL injuries and use of comprehensive neuromuscular retraining programs such as Sportsmetrics after ACL reconstruction are greatly required in athletes, especially young competitive patients who wish to return to high-risk activities. Patients at particularly high risk of injury are female athletes between the ages of 14 and 18, male athletes between the ages of 19 and 25, and those with a family history of ACL injury. Caution is warranted in counseling patients of realistic RTS rates and potential for injury to either knee.

References

1. Gans I, Retzky JS, Jones LC, Tanaka MJ. Epidemiology of recurrent anterior cruciate ligament injuries in National Collegiate Athletic Association Sports: the injury surveillance program, 2004–2014. Orthop J Sports Med. 2018;6(6):2325967118777823. https://doi.org/10.1177/2325967118777823.
2. Grawe B, Sugiguchi F, Bedi A, Rodeo S. Biology of anterior cruciate ligament graft healing. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 111–24.
3. Smith FW, Rosenlund EA, Aune AK, MacLean JA, Hillis SW. Subjective functional assessments and the return to competitive sport after anterior cruciate ligament reconstruction. Br J Sports Med. 2004;38(3):279–84.
4. Mascarenhas R, Tranovich MJ, Kropf EJ, Fu FH, Harner CD. Bone-patellar tendon-bone autograft versus hamstring autograft anterior cruciate ligament reconstruction in the young athlete: a retrospective matched analysis with 2–10 year follow-up. Knee

Surg Sports Traumatol Arthrosc. 2012;20(8):1520–7. https://doi.org/10.1007/s00167-011-1735-2.
5. Nwachukwu BU, Voleti PB, Berkanish P, Chang B, Cohn MR, Williams RJ 3rd, Allen AA. Return to play and patient satisfaction after ACL reconstruction: study with minimum 2-year follow-up. J Bone Joint Surg Am. 2017;99(9):720–5. https://doi.org/10.2106/JBJS.16.00958.
6. Noyes FR, Mooar PA, Matthews DS, Butler DL. The symptomatic anterior cruciate-deficient knee. Part I: the long-term functional disability in athletically active individuals. J Bone Joint Surg Am. 1983;65(2):154–62.
7. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Am J Sports Med. 2016;44(7):1861–76. https://doi.org/10.1177/0363546515621554.
8. Faltstrom A, Hagglund M, Magnusson H, Forssblad M, Kvist J. Predictors for additional anterior cruciate ligament reconstruction: data from the Swedish national ACL register. Knee Surg Sports Traumatol Arthrosc. 2016;24(3):885–94. https://doi.org/10.1007/s00167-014-3406-6.
9. Kay J, Memon M, Marx RG, Peterson D, Simunovic N, Ayeni OR. Over 90% of children and adolescents return to sport after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Knee Surg Sports Traumatol Arthrosc. 2018;26(4):1019–36. https://doi.org/10.1007/s00167-018-4830-9.
10. Faltstrom A, Hagglund M, Kvist J. Patient-reported knee function, quality of life, and activity level after bilateral anterior cruciate ligament injuries. Am J Sports Med. 2013;41(12):2805–13. https://doi.org/10.1177/0363546513502309.
11. Goddard M, Salmon L, Waller A, Papapetros E, Pinczewski LA. Incidence of graft rupture 15 years after bilateral anterior cruciate ligament reconstructions: a case-control study. Bone Joint J. 2013;95-B(6):798–802. https://doi.org/10.1302/0301-620X.95B6.30841.
12. Ristic V, Ristic S, Maljanovic M, Milankov V, Harhaji V, Duricin A. Quality of life after bilateral anterior cruciate ligament reconstructions. Med Pregl. 2015;68(9–10):308–15.
13. Webster KE, Feller JA, Kimp AJ, Whitehead TS. Low rates of return to Preinjury sport after bilateral anterior cruciate ligament reconstruction. Am J Sports Med. 2018; https://doi.org/10.1177/0363546518813901.
14. Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. Arthroscopy. 2011;27(12):1697–705. https://doi.org/10.1016/j.arthro.2011.09.009.
15. Welling W, Benjaminse A, Seil R, Lemmink K, Zaffagnini S, Gokeler A. Low rates of patients meeting return to sport criteria 9 months after anterior cruciate ligament reconstruction: a prospective longitudinal study. Knee Surg Sports Traumatol Arthrosc. 2018;26(12):3636–44. https://doi.org/10.1007/s00167-018-4916-4.
16. Herbst E, Hoser C, Hildebrandt C, Raschner C, Hepperger C, Pointner H, Fink C. Functional assessments for decision-making regarding return to sports following ACL reconstruction. Part II: clinical application of a new test battery. Knee Surg Sports Traumatol Arthrosc. 2015;23(5):1283–91. https://doi.org/10.1007/s00167-015-3546-3.
17. Logerstedt D, Di Stasi S, Grindem H, Lynch A, Eitzen I, Engebretsen L, Risberg MA, Axe MJ, Snyder-Mackler L. Self-reported knee function can identify athletes who fail return-to-activity criteria up to 1 year after anterior cruciate ligament reconstruction: a Delaware-Oslo ACL cohort study. J Orthop Sports Phys Ther. 2014;44(12):914–23. https://doi.org/10.2519/jospt.2014.4852.
18. Garrison JC, Shanley E, Thigpen C, Geary R, Osler M, Delgiorno J. The reliability of the Vail sport test as a measure of physical performance following anterior cruciate ligament reconstruction. Int J Sports Phys Ther. 2012;7(1):20–30.
19. Hildebrandt C, Muller L, Zisch B, Huber R, Fink C, Raschner C. Functional assessments for decision-making regarding return to sports following ACL reconstruction. Part I: development of a new test battery. Knee Surg Sports Traumatol Arthrosc. 2015;23(5):1273–81. https://doi.org/10.1007/s00167-015-3529-4.
20. Takazawa Y, Ikeda H, Saita Y, Kawasaki T, Ishijima M, Nagayama M, Kaneko H, Kaneko K. Return to play of Rugby players after anterior cruciate ligament reconstruction using hamstring autograft: return to sports and graft failure according to age. Arthroscopy. 2017;33(1):181–9. https://doi.org/10.1016/j.arthro.2016.06.009.
21. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med. 2016;50(13):804–8. https://doi.org/10.1136/bjsports-2016-096031.
22. Nawasreh Z, Logerstedt D, Cummer K, Axe M, Risberg MA, Snyder-Mackler L. Functional performance 6 months after ACL reconstruction can predict return to participation in the same preinjury activity level 12 and 24 months after surgery. Br J Sports Med. 2018;52(6):375. https://doi.org/10.1136/bjsports-2016-097095.
23. Salmon LJ, Heath E, Akrawi H, Roe JP, Linklater J, Pinczewski LA. 20-year outcomes of anterior cruciate ligament reconstruction with hamstring tendon autograft: the catastrophic effect of age and posterior Tibial slope. Am J Sports Med. 2018;46(3):531–43. https://doi.org/10.1177/0363546517741497.
24. Bourke HE, Salmon LJ, Waller A, Patterson V, Pinczewski LA. Survival of the anterior cruciate ligament graft and the contralateral ACL at a minimum of 15 years. Am J Sports Med. 2012;40(9):1985–92. https://doi.org/10.1177/0363546512454414.

25. Brophy RH, Schmitz L, Wright RW, Dunn WR, Parker RD, Andrish JT, McCarty EC, Spindler KP. Return to play and future ACL injury risk after ACL reconstruction in soccer athletes from the Multicenter orthopaedic outcomes network (MOON) group. Am J Sports Med. 2012;40(11):2517–22. https://doi.org/10.1177/0363546512459476.
26. Allen MM, Pareek A, Krych AJ, Hewett T, Levy BA, Stuart MJ, Dahm DL. Are female soccer players at an increased risk of second anterior cruciate ligament injury compared with their athletic peers? Am J Sports Med. 2016; https://doi.org/10.1177/0363546516648439.
27. Failla MJ, Logerstedt DS, Grindem H, Axe MJ, Risberg MA, Engebretsen L, Huston LJ, Spindler KP, Snyder-Mackler L. Does extended preoperative rehabilitation influence outcomes 2 years after ACL reconstruction? A comparative effectiveness study between the MOON and Delaware-Oslo ACL cohorts. Am J Sports Med. 2016;44(10):2608–14. https://doi.org/10.1177/0363546516652594.
28. Almeida A, Valin MR, Ferreira R, de Almeida NC, Agostini AP. Correlation between the result from arthroscopic reconstruction of the anterior cruciate ligament of the knee and the return to sports activity. Rev Bras Ortop. 2014;49(3):240–4. https://doi.org/10.1016/j.rboe.2014.02.006.
29. Beischer S, Senorski EH, Thomee C, Samuelsson K, Thomee R. Young athletes return too early to knee-strenuous sport, without acceptable knee function after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2018;26(7):1966–74. https://doi.org/10.1007/s00167-017-4747-8.
30. Laboute E, Savalli L, Puig P, Trouve P, Sabot G, Monnier G, Dubroca B. Analysis of return to competition and repeat rupture for 298 anterior cruciate ligament reconstructions with patellar or hamstring tendon autograft in sportspeople. Ann Phys Rehabil Med. 2010;53(10):598–614. https://doi.org/10.1016/j.rehab.2010.10.002.
31. Lefevre N, Klouche S, Mirouse G, Herman S, Gerometta A, Bohu Y. Return to sport after primary and revision anterior cruciate ligament reconstruction: a prospective comparative study of 552 patients from the FAST cohort. Am J Sports Med. 2017;45(1):34–41. https://doi.org/10.1177/0363546516660075.
32. Ardern CL, Taylor NF, Feller JA, Webster KE. Return-to-sport outcomes at 2 to 7 years after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2012;40(1):41–8. https://doi.org/10.1177/0363546511422999.
33. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Sports participation 2 years after anterior cruciate ligament reconstruction in athletes who had not returned to sport at 1 year: a prospective follow-up of physical function and psychological factors in 122 athletes. Am J Sports Med. 2015;43(4):848–56. https://doi.org/10.1177/0363546514563282.
34. Rosso F, Bonasia DE, Cottino U, Cambursano S, Dettoni F, Rossi R. Factors affecting subjective and objective outcomes and return to play in anterior cruciate ligament reconstruction: a retrospective cohort study. Joints. 2018;6(1):23–32. https://doi.org/10.1055/s-0038-1636931.
35. Hamrin Senorski E, Svantesson E, Beischer S, Thomee C, Thomee R, Karlsson J, Samuelsson K. Low 1-year return-to-sport rate after anterior cruciate ligament reconstruction regardless of patient and surgical factors: a prospective cohort study of 272 patients. Am J Sports Med. 2018;46(7):1551–8. https://doi.org/10.1177/0363546518765120.
36. Lentz TA, Zeppieri G Jr, Tillman SM, Indelicato PA, Moser MW, George SZ, Chmielewski TL. Return to preinjury sports participation following anterior cruciate ligament reconstruction: contributions of demographic, knee impairment, and self-report measures. J Orthop Sports Phys Ther. 2012;42(11):893–901. https://doi.org/10.2519/jospt.2012.4077.
37. Novaretti JV, Franciozi CE, Forgas A, Sasaki PH, Ingham SJM, Abdalla RJ. Quadriceps strength deficit at 6 months after ACL reconstruction does not predict return to Preinjury sports level. Sports Health. 2018;10(3):266–71. https://doi.org/10.1177/1941738118759911.
38. Sousa PL, Krych AJ, Cates RA, Levy BA, Stuart MJ, Dahm DL. Return to sport: does excellent 6-month strength and function following ACL reconstruction predict midterm outcomes? Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1356–63. https://doi.org/10.1007/s00167-015-3697-2.
39. Rodriguez-Roiz JM, Caballero M, Ares O, Sastre S, Lozano L, Popescu D. Return to recreational sports activity after anterior cruciate ligament reconstruction: a one- to six-year follow-up study. Arch Orthop Trauma Surg. 2015;135(8):1117–22. https://doi.org/10.1007/s00402-015-2240-8.
40. Langford JL, Webster KE, Feller JA. A prospective longitudinal study to assess psychological changes following anterior cruciate ligament reconstruction surgery. Br J Sports Med. 2009;43(5):377–8. https://doi.org/10.1136/bjsm.2007.044818.
41. Devgan A, Magu NK, Siwach RC, Rohilla RK, Sangwan SS. Functional outcome in athletes at five years of arthroscopic anterior cruciate ligament reconstruction. ISRN Orthop. 2011;2011:1–6.
42. Dunn WR, Spindler KP. Predictors of activity level 2 years after anterior cruciate ligament reconstruction (ACLR): a Multicenter orthopaedic outcomes network (MOON) ACLR cohort study. Am J Sports Med. 2010;38(10):2040–50. https://doi.org/10.1177/0363546510370280.
43. Sandon A, Werner S, Forssblad M. Factors associated with returning to football after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2015;23(9):2514–21. https://doi.org/10.1007/s00167-014-3023-4.
44. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-

thirds of patients have not returned by 12 months after surgery. Am J Sports Med. 2011;39(3):538–43. https://doi.org/10.1177/0363546510384798.
45. Faltstrom A, Hagglund M, Kvist J. Factors associated with playing football after anterior cruciate ligament reconstruction in female football players. Scand J Med Sci Sports. 2016;26(11):1343–52. https://doi.org/10.1111/sms.12588.
46. Hamrin Senorski E, Samuelsson K, Thomee C, Beischer S, Karlsson J, Thomee R. Return to knee-strenuous sport after anterior cruciate ligament reconstruction: a report from a rehabilitation outcome registry of patient characteristics. Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1364–74. https://doi.org/10.1007/s00167-016-4280-1.
47. Webster KE, Feller JA, Hartnett N, Leigh WB, Richmond AK. Comparison of patellar tendon and hamstring tendon anterior cruciate ligament reconstruction: a 15-year follow-up of a randomized controlled trial. Am J Sports Med. 2016;44(1):83–90. https://doi.org/10.1177/0363546515611886.
48. Noyes FR, Barber-Westin SD. A comparison of results in acute and chronic anterior cruciate ligament ruptures of arthroscopically assisted autogenous patellar tendon reconstruction. Am J Sports Med. 1997;25(4):460–71.
49. Barber-Westin SD, Noyes FR, Andrews M. A rigorous comparison between the sexes of results and complications after anterior cruciate ligament reconstruction. Am J Sports Med. 1997;25(4):514–26.
50. Faltstrom A, Kvist J, Gauffin H, Hagglund M. Female soccer players with anterior cruciate ligament reconstruction have a higher risk of new knee injuries and quit soccer to a higher degree than knee-healthy controls. Am J Sports Med. 2019;47(1):31–40. https://doi.org/10.1177/0363546518808006.
51. Webster KE, Feller JA. Exploring the high Reinjury rate in younger patients undergoing anterior cruciate ligament reconstruction. Am J Sports Med. 2016;44(11):2827–32. https://doi.org/10.1177/0363546516651845.
52. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. Am J Sports Med. 2014;42(7):1567–73. https://doi.org/10.1177/0363546514530088.
53. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med. 2009;37(2):246–51.
54. Webster KE, Feller JA, Leigh WB, Richmond AK. Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. Am J Sports Med. 2014;42(3):641–7. https://doi.org/10.1177/0363546513517540.
55. Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, Consortium M, Spindler KP. Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: prospective analysis of 2488 primary ACL reconstructions from the MOON cohort. Am J Sports Med. 2015;43(7):1583–90. https://doi.org/10.1177/0363546515578836.
56. Andernord D, Desai N, Bjornsson H, Ylander M, Karlsson J, Samuelsson K. Patient predictors of early revision surgery after anterior cruciate ligament reconstruction: a cohort study of 16,930 patients with 2-year follow-up. Am J Sports Med. 2015;43(1):121–7. https://doi.org/10.1177/0363546514552788.
57. Borchers JR, Pedroza A, Kaeding C. Activity level and graft type as risk factors for anterior cruciate ligament graft failure: a case-control study. Am J Sports Med. 2009;37(12):2362–7. https://doi.org/10.1177/0363546509340633.
58. Kocher MS, Smith JT, Zoric BJ, Lee B, Micheli LJ. Transphyseal anterior cruciate ligament reconstruction in skeletally immature pubescent adolescents. J Bone Joint Surg Am. 2007;89(12):2632–9.
59. Cassard X, Cavaignac E, Maubisson L, Bowen M. Anterior cruciate ligament reconstruction in children with a quadrupled semitendinosus graft: preliminary results with minimum 2 years of follow-up. J Pediatr Orthop. 2014;34(1):70–7. https://doi.org/10.1097/BPO.0b013e3182a008b6.
60. Hui C, Roe J, Ferguson D, Waller A, Salmon L, Pinczewski L. Outcome of anatomic transphyseal anterior cruciate ligament reconstruction in Tanner stage 1 and 2 patients with open physes. Am J Sports Med. 2012;40(5):1093–8. https://doi.org/10.1177/0363546512438508.
61. Redler LH, Caldwell JM, Schulz BM, Levine WN. Management of articular cartilage defects of the knee. Phys Sportsmed. 2012;40(1):20–35. https://doi.org/10.3810/psm.2012.02.1948.
62. Cordasco FA, Mayer SW, Green DW. All-inside, all-epiphyseal anterior cruciate ligament reconstruction in skeletally immature athletes: return to sport, incidence of second surgery, and 2-year clinical outcomes. Am J Sports Med. 2017;45(4):856–63. https://doi.org/10.1177/0363546516677723.
63. Edwards PH, Grana WA. Anterior cruciate ligament reconstruction in the immature athlete: long-term results of intra-articular reconstruction. Am J Knee Surg. 2001;14(4):232–7.
64. Graziano J, Chiaia T, de Mille P, Nawabi DH, Green DW, Cordasco FA. Return to sport for skeletally immature athletes after ACL reconstruction: preventing a second injury using a quality of movement assessment and quantitative measures to address modifiable risk factors. Orthop J Sports Med. 2017;5(4):2325967117700599. https://doi.org/10.1177/2325967117700599.
65. Calvo R, Figueroa D, Gili F, Vaisman A, Mococain P, Espinosa M, Leon A, Arellano S. Transphyseal anterior cruciate ligament reconstruction in patients with open physes: 10-year follow-up study. Am J Sports Med. 2015;43(2):289–94. https://doi.org/10.1177/0363546514557939.
66. Cohen M, Ferretti M, Quarteiro M, Marcondes FB, de Hollanda JP, Amaro JT, Abdalla RJ. Transphyseal anterior cruciate ligament reconstruction in patients

with open physes. Arthroscopy. 2009;25(8):831–8. https://doi.org/10.1016/j.arthro.2009.01.015.
67. Dei Giudici L, Fabbrini R, Garro L, Arima S, Gigante A, Tucciarone A. Arthroscopic transphyseal anterior cruciate ligament reconstruction in adolescent athletes. J Orthop Surg (Hong Kong). 2016;24(3):307–11. https://doi.org/10.1177/1602400307.
68. Shelbourne KD, Sullivan AN, Bohard K, Gray T, Urch SE. Return to basketball and soccer after anterior cruciate ligament reconstruction in competitive school-aged athletes. Sports Health. 2009;1(3):236–41. https://doi.org/10.1177/1941738109334275.
69. Goddard M, Bowman N, Salmon LJ, Waller A, Roe JP, Pinczewski LA. Endoscopic anterior cruciate ligament reconstruction in children using living donor hamstring tendon allografts. Am J Sports Med. 2013; https://doi.org/10.1177/0363546512473576.
70. Dekker TJ, Godin JA, Dale KM, Garrett WE, Taylor DC, Riboh JC. Return to sport after Pediatric anterior cruciate ligament reconstruction and its effect on subsequent anterior cruciate ligament injury. J Bone Joint Surg Am. 2017;99(11):897–904. https://doi.org/10.2106/JBJS.16.00758.
71. Aronowitz ER, Ganley TJ, Goode JR, Gregg JR, Meyer JS. Anterior cruciate ligament reconstruction in adolescents with open physes. Am J Sports Med. 2000;28(2):168–75.
72. Nikolaou P, Kalliakmanis A, Bousgas D, Zourntos S. Intraarticular stabilization following anterior cruciate ligament injury in children and adolescents. Knee Surg Sports Traumatol Arthrosc. 2011;19(5):801–5. https://doi.org/10.1007/s00167-010-1375-y.
73. Larson CM, Heikes CS, Ellingson CI, Wulf CA, Giveans MR, Stone RM, Bedi A. Allograft and autograft Transphyseal anterior cruciate ligament reconstruction in skeletally immature patients: outcomes and complications. Arthroscopy. 2016;32(5):860–7. https://doi.org/10.1016/j.arthro.2015.10.014.
74. Webster KE, Feller JA, Whitehead TS, Myer GD, Merory PB. Return to sport in the younger patient with anterior cruciate ligament reconstruction. Orthop J Sports Med. 2017;5(4):2325967117703399. https://doi.org/10.1177/2325967117703399.
75. Chicorelli AM, Micheli LJ, Kelly M, Zurakowski D, MacDougall R. Return to sport after anterior cruciate ligament reconstruction in the skeletally immature athlete. Clin J Sport Med. 2016;26(4):266–71. https://doi.org/10.1097/jsm.0000000000000275.
76. Morgan MD, Salmon LJ, Waller A, Roe JP, Pinczewski LA. Fifteen-year survival of endoscopic anterior cruciate ligament reconstruction in patients aged 18 years and younger. Am J Sports Med. 2016;44(2):384–92. https://doi.org/10.1177/0363546515623032.
77. Placella G, Bartoli M, Peruzzi M, Speziali A, Pace V, Cerulli G. Return to sport activity after anterior cruciate ligament reconstruction in skeletally immature athletes with manual drilling original all inside reconstruction at 8 years follow-up. Acta Orthop Traumatol Turc. 2016;50(6):635–8. https://doi.org/10.1016/j.aott.2016.03.006.
78. Holwein C, Hinterwimmer S, Mayr HO, Lammle L, Brucker PU, Munch EO, Imhoff AB. Functional outcome after transphyseal anterior cruciate ligament reconstruction in young patients with open growth plates. Knee. 2016;23(6):1121–32. https://doi.org/10.1016/j.knee.2016.09.001.
79. McCullough KA, Phelps KD, Spindler KP, Matava MJ, Dunn WR, Parker RD, Group M, Reinke EK. Return to high school- and college-level football after anterior cruciate ligament reconstruction: a Multicenter orthopaedic outcomes network (MOON) cohort study. Am J Sports Med. 2012;40(11):2523–9. https://doi.org/10.1177/0363546512456836.
80. Schmale GA, Kweon C, Larson RV, Bompadre V. High satisfaction yet decreased activity 4 years after transphyseal ACL reconstruction. Clin Orthop Relat Res. 2014;472(7):2168–74. https://doi.org/10.1007/s11999-014-3561-6.
81. Fauno P, Rahr-Wagner L, Lind M. Risk for revision after anterior cruciate ligament reconstruction is higher among adolescents: results from the Danish registry of knee ligament reconstruction. Orthop J Sports Med. 2014;2(10):2325967114552405. https://doi.org/10.1177/2325967114552405.
82. Kamath GV, Murphy T, Creighton RA, Viradia N, Taft TN, Spang JT. Anterior cruciate ligament injury, return to play, and Reinjury in the elite collegiate athlete: analysis of an NCAA division I cohort. Am J Sports Med. 2014;42(7):1638–43. https://doi.org/10.1177/0363546514524164.
83. Howard JS, Lembach ML, Metzler AV, Johnson DL. Rates and determinants of return to play after anterior cruciate ligament reconstruction in National Collegiate Athletic Association Division I Soccer Athletes: a study of the Southeastern conference. Am J Sports Med. 2016;44(2):433–9. https://doi.org/10.1177/0363546515614315.
84. Daruwalla JH, Greis PE, Hancock R, Group ASPC, Xerogeanes JW. Rates and determinants of return to play after anterior cruciate ligament reconstruction in NCAA division 1 college football athletes: a study of the ACC, SEC, and PAC-12 conferences. Orthop J Sports Med. 2014;2(8):2325967114543901. https://doi.org/10.1177/2325967114543901.
85. Mai HT, Chun DS, Schneider AD, Erickson BJ, Freshman RD, Kester B, Verma NN, Hsu WK. Performance-based outcomes after anterior cruciate ligament reconstruction in professional athletes differ between sports. Am J Sports Med. 2017;45(10):2226–32. https://doi.org/10.1177/0363546517704834.
86. Cinque ME, Hannon CP, Bohl DD, Erickson BJ, Verma NN, Cole BJ, Bach BR Jr. Return to sport and performance after anterior cruciate ligament reconstruction in National Football League Linemen. Orthop J Sports Med. 2017;5(6):2325967117711681. https://doi.org/10.1177/2325967117711681.
87. Read CR, Aune KT, Cain EL Jr, Fleisig GS. Return to play and decreased performance after anterior cruciate ligament reconstruction in National

Football League Defensive Players. Am J Sports Med. 2017;45(8):1815–21. https://doi.org/10.1177/0363546517703361.
88. Erickson BJ, Harris JD, Heninger JR, Frank R, Bush-Joseph CA, Verma NN, Cole BJ, Bach BR. Performance and return-to-sport after ACL reconstruction in NFL quarterbacks. Orthopedics. 2014;37(8):e728–34. https://doi.org/10.3928/01477447-20140728-59.
89. Carey JL, Huffman GR, Parekh SG, Sennett BJ. Outcomes of anterior cruciate ligament injuries to running backs and wide receivers in the National Football League. Am J Sports Med. 2006;34(12):1911–7. https://doi.org/10.1177/0363546506290186.
90. Yang J, Hodax JD, Machan JT, Secrist ES, Durand WM, Owens BD, Eltorai AEM, Dodson CC. National Football League Skilled and unskilled positions vary in opportunity and yield in return to play after an anterior cruciate ligament injury. Orthop J Sports Med. 2017;5(9):2325967117729334. https://doi.org/10.1177/2325967117729334.
91. Eisenstein ED, Rawicki NL, Rensing NJ, Kusnezov NA, Lanzi JT. Variables affecting return to play after anterior cruciate ligament injury in the National Football League. Orthop J Sports Med. 2016;4(10):2325967116670117. https://doi.org/10.1177/2325967116670117.
92. Shah VM, Andrews JR, Fleisig GS, McMichael CS, Lemak LJ. Return to play after anterior cruciate ligament reconstruction in National Football League athletes. Am J Sports Med. 2010;38(11):2233–9. https://doi.org/10.1177/0363546510372798.
93. Harris JD, Erickson BJ, Bach BR Jr, Abrams GD, Cvetanovich GL, Forsythe B, McCormick FM, Gupta AK, Cole BJ. Return-to-sport and performance after anterior cruciate ligament reconstruction in National Basketball Association Players. Sports Health. 2013;5(6):562–8. https://doi.org/10.1177/1941738113495788.
94. Kester BS, Behery OA, Minhas SV, Hsu WK. Athletic performance and career longevity following anterior cruciate ligament reconstruction in the National Basketball Association. Knee Surg Sports Traumatol Arthrosc. 2017;25(10):3031–7. https://doi.org/10.1007/s00167-016-4060-y.
95. Busfield BT, Kharrazi FD, Starkey C, Lombardo SJ, Seegmiller J. Performance outcomes of anterior cruciate ligament reconstruction in the National Basketball Association. Arthroscopy. 2009;25(8):825–30. https://doi.org/10.1016/j.arthro.2009.02.021.
96. Erickson BJ, Harris JD, Cvetanovich GL, Bach BR, Bush-Joseph CA, Abrams GD, Gupta AK, McCormick FM, Cole BJ. Performance and return to sport after anterior cruciate ligament reconstruction in male Major League Soccer players. Orthop J Sports Med. 2013;1(2):2325967113497189. https://doi.org/10.1177/2325967113497189.
97. Walden M, Hagglund M, Magnusson H, Ekstrand J. ACL injuries in men's professional football: a 15-year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture. Br J Sports Med. 2016;50(12):744–50. https://doi.org/10.1136/bjsports-2015-095952.
98. Zaffagnini S, Grassi A, Marcheggiani Muccioli GM, Tsapralis K, Ricci M, Bragonzoni L, Della Villa S, Marcacci M. Return to sport after anterior cruciate ligament reconstruction in professional soccer players. Knee. 2014;21(3):731–5. https://doi.org/10.1016/j.knee.2014.02.005.
99. Fabricant PD, Chin CS, Conte S, Coleman SH, Pearle AD, Dines JS. Return to play after anterior cruciate ligament reconstruction in major league baseball athletes. Arthroscopy. 2015;31(5):896–900. https://doi.org/10.1016/j.arthro.2014.12.008.
100. Erickson BJ, Harris JD, Cole BJ, Frank RM, Fillingham YA, Ellman MB, Verma NN, Bach BR Jr. Performance and return to sport after anterior cruciate ligament reconstruction in National Hockey League Players. Orthop J Sports Med. 2014;2(9):2325967114548831. https://doi.org/10.1177/2325967114548831.
101. Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. Br J Sports Med. 2016; https://doi.org/10.1136/bjsports-2015-095908.
102. Lai CCH, Feller JA, Webster KE. Fifteen-year audit of anterior cruciate ligament reconstructions in the Australian football league from 1999 to 2013: return to play and subsequent ACL injury. Am J Sports Med. 2018;46(14):3353–60. https://doi.org/10.1177/0363546518803932.
103. Namdari S, Scott K, Milby A, Baldwin K, Lee GC. Athletic performance after ACL reconstruction in the Women's National Basketball Association. Phys Sportsmed. 2011;39(1):36–41. https://doi.org/10.3810/psm.2011.02.1860.
104. Ajuied A, Wong F, Smith C, Norris M, Earnshaw P, Back D, Davies A. Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. Am J Sports Med. 2014;42(9):2242–52. https://doi.org/10.1177/0363546513508376.
105. Bigoni M, Sacerdote P, Turati M, Franchi S, Gandolla M, Gaddi D, Moretti S, Munegato D, Augusti CA, Bresciani E, Omeljaniuk RJ, Locatelli V, Torsello A. Acute and late changes in intraarticular cytokine levels following anterior cruciate ligament injury. J Orthop Res. 2013;31(2):315–21. https://doi.org/10.1002/jor.22208.
106. Claes S, Hermie L, Verdonk R, Bellemans J, Verdonk P. Is osteoarthritis an inevitable consequence of anterior cruciate ligament reconstruction? A meta-analysis. Knee Surg Sports Traumatol Arthrosc. 2013;21(9):1967–76. https://doi.org/10.1007/s00167-012-2251-8.
107. Barenius B, Ponzer S, Shalabi A, Bujak R, Norlen L, Eriksson K. Increased risk of osteoarthritis after anterior cruciate ligament reconstruction: a 14-year

follow-up study of a randomized controlled trial. Am J Sports Med. 2014;42(5):1049–57. https://doi.org/10.1177/0363546514526139.
108. Li RT, Lorenz S, Xu Y, Harner CD, Fu FH, Irrgang JJ. Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. Am J Sports Med. 2011;39(12):2595–603. https://doi.org/10.1177/0363546511424720.
109. Smith MV, Nepple JJ, Wright RW, Matava MJ, Brophy RH. Knee osteoarthritis is associated with previous meniscus and anterior cruciate ligament surgery among elite college American football athletes. Sports Health. 2017;9(3):247–51. https://doi.org/10.1177/1941738116683146.
110. Theologis AA, Kuo D, Cheng J, Bolbos RI, Carballido-Gamio J, Ma CB, Li X. Evaluation of bone bruises and associated cartilage in anterior cruciate ligament-injured and -reconstructed knees using quantitative t(1rho) magnetic resonance imaging: 1-year cohort study. Arthroscopy. 2011;27(1):65–76. https://doi.org/10.1016/j.arthro.2010.06.026.
111. Hui C, Salmon LJ, Kok A, Maeno S, Linklater J, Pinczewski LA. Fifteen-year outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft for "isolated" anterior cruciate ligament tear. Am J Sports Med. 2011;39(1):89–98. https://doi.org/10.1177/0363546510379975.
112. Potter HG, Jain SK, Ma Y, Black BR, Fung S, Lyman S. Cartilage injury after acute, isolated anterior cruciate ligament tear: immediate and longitudinal effect with clinical/MRI follow-up. Am J Sports Med. 2012;40(2):276–85. https://doi.org/10.1177/0363546511423380.
113. Struglics A, Larsson S, Kumahashi N, Frobell R, Lohmander LS. Changes in cytokines and Aggrecan ARGS Neoepitope in synovial fluid and serum and in C-terminal crosslinking Telopeptide of type II collagen and N-terminal crosslinking Telopeptide of type I collagen in urine over five years after anterior cruciate ligament rupture: an exploratory analysis in the knee anterior cruciate ligament, nonsurgical versus surgical treatment trial. Arthritis Rheumatol. 2015;67(7):1816–25. https://doi.org/10.1002/art.39146.
114. Van Ginckel A, Verdonk P, Victor J, Witvrouw E. Cartilage status in relation to return to sports after anterior cruciate ligament reconstruction. Am J Sports Med. 2013;41(3):550–9. https://doi.org/10.1177/0363546512473568.
115. Van Ginckel A, Verdonk P, Witvrouw E. Cartilage adaptation after anterior cruciate ligament injury and reconstruction: implications for clinical management and research? A systematic review of longitudinal MRI studies. Osteoarthr Cartil. 2013;21(8):1009–24. https://doi.org/10.1016/j.joca.2013.04.015.
116. MARS Group. Meniscal and articular cartilage predictors of clinical outcome after revision anterior cruciate ligament reconstruction. Am J Sports Med. 2016;44(7):1671–9. https://doi.org/10.1177/0363546516644218.
117. Brophy RH, Haas AK, Huston LJ, Nwosu SK, Group M, Wright RW. Association of Meniscal Status, lower extremity alignment, and body mass index with Chondrosis at revision anterior cruciate ligament reconstruction. Am J Sports Med. 2015;43(7):1616–22. https://doi.org/10.1177/0363546515578838.
118. Johnson WR, Makani A, Wall AJ, Hosseini A, Hampilos P, Li G, TJt G. Patient outcomes and predictors of success after revision anterior cruciate ligament reconstruction. Orthop J Sports Med. 2015;3(10):2325967115611660. https://doi.org/10.1177/2325967115611660.
119. Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: graft options and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 221–57. https://doi.org/10.1016/b978-0-323-32903-3.00008-1.
120. Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: results using a quadriceps tendon-patellar bone autograft. Am J Sports Med. 2006;34(4):553–64. https://doi.org/10.1177/0363546505281812.
121. Noyes FR, Barber-Westin SD. Revision anterior cruciate surgery with use of bone-patellar tendon-bone autogenous grafts. J Bone Joint Surg Am. 2001;83-A(8):1131–43.
122. Noyes FR, Barber-Westin SD. Revision anterior cruciate ligament reconstruction: report of 11-year experience and results in 114 consecutive patients. Instr Course Lect. 2001;50:451–61.
123. Ahmed I, Salmon L, Roe J, Pinczewski L. The long-term clinical and radiological outcomes in patients who suffer recurrent injuries to the anterior cruciate ligament after reconstruction. Bone Joint J. 2017;99-b(3):337–43. https://doi.org/10.1302/0301-620x.99b3.37863.
124. Ahn JH, Kim JG, Wang JH, Jung CH, Lim HC. Long-term results of anterior cruciate ligament reconstruction using bone-patellar tendon-bone: an analysis of the factors affecting the development of osteoarthritis. Arthroscopy. 2012;28(8):1114–23. https://doi.org/10.1016/j.arthro.2011.12.019.
125. Gerhard P, Bolt R, Duck K, Mayer R, Friederich NF, Hirschmann MT. Long-term results of arthroscopically assisted anatomical single-bundle anterior cruciate ligament reconstruction using patellar tendon autograft: are there any predictors for the development of osteoarthritis? Knee Surg Sports Traumatol Arthrosc. 2013;21(4):957–64. https://doi.org/10.1007/s00167-012-2001-y.
126. Keays SL, Newcombe PA, Bullock-Saxton JE, Bullock MI, Keays AC. Factors involved in the development of osteoarthritis after anterior cruciate ligament surgery. Am J Sports Med. 2010;38(3):455–63. https://doi.org/10.1177/0363546509350914.
127. Nakata K, Shino K, Horibe S, Tanaka Y, Toritsuka Y, Nakamura N, Koyanagi M, Yoshikawa H. Arthroscopic anterior cruciate ligament recon-

struction using fresh-frozen bone plug-free allogeneic tendons: 10-year follow-up. Arthroscopy. 2008;24(3):285–91.
128. Salmon LJ, Russell VJ, Refshauge K, Kader D, Connolly C, Linklater J, Pinczewski LA. Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. Am J Sports Med. 2006;34(5):721–32.
129. Shelbourne KD, Gray T. Minimum 10-year results after anterior cruciate ligament reconstruction: how the loss of normal knee motion compounds other factors related to the development of osteoarthritis after surgery. Am J Sports Med. 2009;37(3):471–80. https://doi.org/10.1177/0363546508326709.
130. Ellis HB, Matheny LM, Briggs KK, Pennock AT, Steadman JR. Outcomes and revision rate after bone-patellar tendon-bone allograft versus autograft anterior cruciate ligament reconstruction in patients aged 18 years or younger with closed physes. Arthroscopy. 2012;28(12):1819–25. https://doi.org/10.1016/j.arthro.2012.06.016.

Part III

Spectrum of Optimal Treatment of ACL Injuries

7 What Is the Scientific Basis for Knee Ligament Healing and Maturation to Restore Biomechanical Properties and a Return to Sport?

Andrew Smith and Frank R. Noyes

7.1 ACL Anatomy: Native Tendon-Bone Insertion

The attachment of the native ACL is very similar to many other ligaments found within the body in that it is made of highly specialized, dense connective tissue that spans joints and connects bones. Key differences found in the ACL are that it is both intraarticular and extrasynovial. The native ACL has a vascular and neural network that is woven throughout several fascicular collagen bundles within a synovial sheath [1]. This neural network is thought to provide proprioceptive feedback to allow for position sense and balance; however, the clinical significance of these findings is not entirely delineated [2]. With primarily a direct insertion into the bone, the ACL transitions from ligamentous bony structure through collagen interdigitation. This occurs over a narrow 1-mm transition zone consisting of tendon, unmineralized fibrocartilage, mineralized fibrocartilage, and bone [1, 3–5]. As the stiffness changes throughout the attachment, this provides for an ideal biomechanical environment for gradual stress distribution and differential tensioning throughout a complex loading process. The effects of stress concentration are minimized by gradual changes from the compliant ligament to the stiff bone. These distinct transitional zones surround the collagen fibers in differing mediums offering a mechanical advantage during loading [6]. At the fibrocartilage insertion site, there are cartilage-specific collagen types II, IX, X, and XI. Type X collagen maintains the interface between mineralized and unmineralized fibrocartilage. All ACL reconstructions require tendon-bone healing along the entire course of the reconstructed ligament within an osseous tunnel created at the time of surgery. Notably, modern day ACL reconstruction techniques do not truly reproduce a native ACL insertional structure or composition.

A. Smith · F. R. Noyes (✉)
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

7.2 Why Does the Injured ACL Not Heal?

After injury and subsequent disruption of ACL fiber continuity, a true reparative healing response does not occur as it does in various other locations in the human body. The intraarticular nature of the ligament is one of main reasons behind its inability to heal. In synovial fluid, there are protease precursors which include plasminogen. In an uninjured knee, plasminogen is inactive. Once ACL injury occurs, urokinase plasminogen activator (uPa) is upregulated by synoviocytes which converts plasminogen to plasmin. The intraarticular bleeding as a result of ligament tearing allows fibrinogen to be acted upon by plasmin

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_7

leading to fibrinolysis. A robust clot of fibrin and platelet elements is never forged, and thus a natural, biological scaffold cannot be formed [7]. Murray et al. [8] noted the presence of an epiligamentous reparative phase of healing. In and around the residual stump after injury is a synovial tissue layer that contains a contractile actin isoform. As this synovial and vascularized tissue begins its own healing process around the native stump tissue mop ends, it encases, thickens, and eventually contracts around each end of the stump. Once this process occurs around the epiligament, any reparative bridging tissue from one end of the failed ligament to the other is not possible due to the contractile nature of this tissue. This synovial layer that forms around the stump in response to injury is deleterious to end-to-end healing of the failed ligament [8]. An empty space is thus formed between the two nonbridging ACL stumps.

Primary repair of the torn ACL was historically a treatment option. A variety of surgical techniques to suture the torn ends of the ligament have been described. High rates of knee laxity and failure have been found at both short- and long-term follow-up in primary repairs [9–12]. Despite historically inferior outcomes of ACL repair, there has been renewed interest with the use of suture anchors and primary repair using biological augmentation in children showing early success [13, 14]. Currently, ACL reconstructive techniques with autograft tendons have been adopted and are currently accepted as the standard of care for treatment. The biological healing of ACL autograft reconstruction will be the primary focus of this chapter.

7.3 Historical Perspective on the Concept of Ligamentization

Investigational studies first looking at the process of graft incorporation confirmed graft viability and noted that successful grafts have the histological appearance of a "normal ligament" [15]. These studies were based mainly on subjective impression without a true definition of what is "normal" both biologically and histologically. Despite the gross similarities, it was not until work done by Amiel and others [16] in 1984 was this further elucidated. A change in environmental and mechanical forces leads to an adaptation in the metabolism and organization of the tissue with respect to the source of nutrition and progenitor and reparative cellular processes [16].

Amiel et al. [16] described the gross, histological, and biochemical transformational changes exhibited by reconstructed ACLs in rabbit models with patellar tendon (PT) autografts. They assessed graft incorporation, viability, and nutrition of the transplanted tissue following reconstruction. Due to the graft's response to intrasynovial milieu and altered biomechanical forces, it was hypothesized that there were accompanying structural and biological changes that occurred within the ligament. Grossly at 4 weeks, the transplanted autografts were swollen two to three times their original size without evidence of a synovial sheath. At 6 weeks, the grafts had decreased swelling and a thin synovial envelope. Histologically, autografts at 2 weeks demonstrated normal crimp, but no central and only peripheral fibroblasts were observed within the tendon. At 4 weeks, cells were no longer concentrated in the peritendinous areas and were homogenously found throughout the matrix of the graft. At 6 weeks, cellularity was greater than either native ACL or PT. A 30-week analysis showed the cellular size and shape was similar to the 6-week time point; however, the relative cell number had decreased to that of a native ACL. Blood vessels were occasionally seen within the graft substance [16].

Collagen composition in the native ACL contains approximately 10% type III collagen, and in autograft tendons, there is no detectable type III collagen. At 30 weeks in Amiel et al.'s [16] experiment, the amount of type III collagen was comparable to that found in a normal ACL. Collagen crosslinking, an important measure of tissue transformation, was nearly similar at 30 weeks and altered from its normal PT composition. It was noted that, in the study time period, the grafts did demonstrate some relaxation and lengthening differences at 2 weeks compared with 30 weeks. The hypothesis was advanced that, during the first 2 weeks, the acellular autograft slightly relaxed and stretched due to its inability to respond to tension, although the amount was not quantified [16].

These authors suggested that once a new ligament is transplanted in the anatomic and environmental milieu of the knee, a ligamentization of the grafted tissue results. Despite the known changes that occur to closely resemble a native ACL, this process needs to be thought of as more of a transformational process and not necessarily a complete restoration of the native ACL. This significant study regarding the basic science of ACL graft healing helped lay the groundwork for future research and understanding.

7.4 Biological Healing of the Graft

This understanding is shaped on the law of functional adaption by Wilhelm Roux in 1905: an organ will adapt itself structurally to an alteration, quantitatively, and qualitatively in function. One of the key components of his theory of developmental mechanics is the difference between self-differentiation and dependent differentiation. With self-differentiation, the inherit structural and functional development of a specific organ or tissue is preprogrammed. Dependent differentiation, on the other hand, attempts to explain how external stimuli can drive purposeful and biological adaptations to tissues to allow for improved function [17, 18].

One of the most challenging aspects of ACL reconstruction remains the biological healing of the graft. The ultimate healing of the graft to bone is a necessary requirement for successful long-term survivorship of the graft [19, 20]. At time point zero after the ACL graft is fixated into the knee with a variety of implants, the initial strength of the graft is superior to the native ACL [19, 20]. Although, if osteointegration and maturation of the graft does not completely occur, these fixation points weaken over time and subsequent graft elongation and failure of the graft or hardware may occur. A properly reconstructed ACL undergoes a complex healing and remodeling process that occurs in two distinct areas which should be evaluated separately: intraarticular remodeling and intra-tunnel graft incorporation (either by tendon-bone or bone-bone healing depending on graft choice). The intraarticular portion of the graft that undergoes the healing process is termed *ligamentization*. As the graft integrates into its host, its intraarticular component experiences functional adaptations and reorganization of its internal structure to closely resemble a native ACL [1, 21–24]. The remodeling of intraarticular and intraosseous graft incorporation dictates function of the joint after ACL reconstruction [25–31].

7.4.1 Phases of Intraarticular Healing

This biological process has been studied in both animal and human models at length. There are three suggested phases of healing that a reconstructed ACL must undergo: early inflammatory phase with central graft necrosis, recellularization/revascularization, and, finally, ligamentization.

7.4.1.1 Early Graft Healing: Graft Necrosis and Early Inflammation

Graft necrosis is a part of the early inflammatory phase of healing thought to take part between the first and fourth week. The early healing cascade has primarily been researched using animal models. This phase is characterized primarily by central acellularity within the graft along with necrosis. Necrosis creates an inflammatory and fibroblastic release of cytokines. Host cells migrate to the graft site and completely replace viable graft cells at approximately 2–4 weeks [23, 32]. Prominent cytokines such as MMP-3, tissue inhibitors of metalloproteinase-1 (TIMP-1), IL-1β, IL-6, IL-8, and TNFα present in the local tissues promote a cascade of growth factor expression which allows for cell migration, proliferation, and extracellular matrix synthesis and eventual revascularization. These chemical mediators disturb the collagen crosslinking patterns leading to myxoid degeneration and interfere with the process of revascularization [1, 33–37]. Grossly, the cross-sectional area of the graft enlarges as it swells to nearly twice the native size of the cruciate ligament [38]. Between the first and second week, the original graft cells are replaced at the graft periphery [23, 39]. The cellular origin of these replacement cells is thought to come from the synovial fluid, native ACL stump, and release of mesenchymal stem cells (MSC) from osseous drilling. It has been theorized that preserving the ACL stump and Hoffa fat pad could be advantageous during this early healing period [1]. The stump tissue is a source of the cellular constituents needed to help repair tissue, including synovial cells and perivascular smooth muscle cells with actin [8].

Collagen composition and structure does not significantly change early. In sheep models, changes have been observed as early at 3 weeks after the procedure [25, 39]. Changes of the collagen molecules and fibrils and pathway of reorganization lead to alterations in mechanical properties during the healing process.

Ineffective healing may result from the presence of persistent inflammation, tendon-bone interface motion, and insufficient number of undifferentiated cells [40]. Macrophage depletion in rat models, reduced fibrovascular scar, and enhanced bone ingrowth improve collagen continuity between tendon and bone. Nonsteroidal anti-inflammatories have also been shown to delay ligament healing [41, 42]. This will be discussed in further detail later in this chapter as one of the main challenges to organized, robust healing.

Graft healing in the femoral and tibial tunnels is also simultaneously occurring in a much different process. Initially, the type of fixation and graft choice governs the initial strength of the construct and influences the subsequent path toward maturation. By 4 weeks, biomechanical studies have shown that failures occur by graft pullout from the tunnels due to the lack of integration of the tissues [25, 43–45]. Compared with the time of initial fixation, there is a weakening of the graft which decreases its strength until about 6 weeks. After that point in time, graft failures transition to occur by an intraarticular mode.

This decrease in graft strength initially during early healing as a result of necrosis has been studied extensively because some authors have suggested that early graft loading should be avoided to prevent failure. Contrary to this understanding, the tensile strength of hamstring and PT reconstructions decrease in groups that are stress deprived as opposed to partially loaded [46–50]. Therefore, graft healing and maturation requires controlled stress to transition effectively into the next phase of healing. Loading the graft early relies on the stability of the graft fixation because adequate healing into bone tunnels has not yet occurred. Alternatively, excessive loading is deleterious to the biological ingrowth and stability that is required to promote effective healing in both the intraarticular ligament and tunnels.

In comparison with animal studies performed in the early healing phase, biopsy studies of ACL grafts in humans at 3 and 6 weeks illustrate that graft necrosis takes place over a much smaller area. Variations in the amount of graft necrosis (complete versus partial), retained native tissue from the grafted source, remodeling speed, neovascularization, and quality of replacement tissue between humans and animals have been demonstrated in comparison studies [51, 52].

Unfortunately, data extrapolated from animal studies must be applied to humans with caution because there are many variables which may be difficult to control. For example, it is difficult to control for weight-bearing in these models. Slight alterations in surgical technique and knee loading mechanics may not truly be applicable to a similar process that occurs in humans. Lastly, the time period over which healing occurs between experimental animals and humans has clear differences that will be specifically discussed in detail.

7.4.1.2 Proliferation and Recellularization

The second phase of healing occurs during the fourth to twelfth week and is the time of the most characteristic adaptations that occur to the graft. This time period is highlighted by the proliferation of cellular activity including fibroblasts and specifically myofibroblasts. These cells are responsible for the robust cellular activity in the graft and substantially surpass that of a native ACL in animal studies [22, 45, 53–55]. Mesenchymal stem cells (MSCs) and fibroblasts group along the periphery of the graft while the central core of the graft remains acellular. These cells are important for exerting cellular tension of the surrounding extracellular matrix and play a role in the crimping structure of collagen fibrils. The concentration of these contractile cells are increasingly found during the first 12 weeks [29, 56]. Cytokines and growth factors like basic fibroblast growth factor (bFGF), TGF-B1, and PDGF allow for graft remodeling to commence. Interestingly, growth factor levels are at their highest levels during the third to sixth week and drop off around the twelfth week [57]. This may not completely explain how the remodeling phase achieves a high capacity for remodeling. The high number of cells present then slowly recedes back to a native ACL cellularity toward the end of this phase.

Collagen fibrils transition from a low to high density, reaching native ACL levels near 12 weeks [45]. The collagen found in a native ACL or hamstring and PT grafts is large in diameter. Interestingly, as graft remodeling commences, the large-diameter fibrils are slowly replaced by small-diameter fibrils in addition to type III collagen [35, 45, 58]. This gives support to why mechanical strength of the grafted ACL is not fully restored even after 2 years of healing [38].

7.4.1.3 Revascularization

As with most intraarticular healing processes, neovascularization is essential to the maturation and reorganization of tissue microarchitecture, structure, and ultimate function. Angiogenic ingrowth is promoted by a potent cell mediator and signal protein called vascular endothelial growth factor (VEGF), which even at 3 weeks can found in reconstructed tissue. The avascular tissue initially creates a relative hypoxia which encourages inflammation, cellular migration, and expression of this growth factor [59]. Revascularization of this tissue promotes a loss and reformation of collagen crimp with increasing type III collagen and fibronectin. These changes correspondingly lead to the weakest mechanical strength of the ligament during healing. The actual extension of vascular microarchitecture proceeds from the periphery of the ligament around the diameter of the graft and is complete near the twelfth week. By approximately 6 months, the vascular density of a reconstructed ACL is similar to a native ACL [55, 60].

It is hypothesized that angiogenesis that occurs during this time period is what allows for the maximal remodeling activity, but this has also been debated in the literature. An application of exogenous VEGF after ACL reconstruction in sheep resulted in an abundance of vascular tissue compared with control groups at 12 weeks [37]. Despite a clear increase in histological vascular and fibroblastic tissue from this application, the stiffness of grafts with exogenous VEGF application was significantly lower, leading to increased laxity in the grafted tendon inferring a potential deleterious effect. It is unclear at this time what the long-term biomechanical influence of a VEGF application would create in humans. Other studies have since demonstrated that maximal proliferation, cellular infiltration, and angiogenesis occur at approximately 6–8 weeks, when the graft's biomechanical properties are at the lowest point in the process of maturation [22, 25, 30, 31, 43–45, 53, 54, 56, 61, 62].

In sheep models using hamstring and PT autografts, the initial necrosis and maturation phases through 12 weeks are similar [1, 31, 63–65]. This has important biomechanical considerations in our understanding of strength and stiffness. As the regularly organized collagen tissues and crimp patterns are progressively lost with high remodeling activity, it is not until the ligamentization phase that collagen crosslinking, fibril orientation, size, and crimp pattern develop [22, 45, 56, 63].

Comparison of animal and human studies of biopsied tissue at 12 weeks after reconstruction demonstrates key similarities and differences. More extensive graft necrosis occurs in animal grafts, while human studies have not demonstrated that >30% of the grafts' cross-sectional area undergoes necrosis. Within these specimens, the unchanged tendinous structure, collagen orientation, and crimp pattern persist suggesting that at least part of the human graft specimens survive throughout the remodeling process [52]. This may be attributed to a more extensive neovascularization process than that which occurs in animals. Around the 6- to 12-month time point, in a variety of animal studies, the previously established peripheral vascular supply is now evenly dispersed throughout the graft [1, 55, 56, 62, 63, 65–68]. In human studies that used gadolinium-enhanced magnetic resonance imaging (MRI) during the course of healing for 2 years, Howell et al. [69] could not detect any central graft revascularization, which remained hypovascular in appearance similar to the posterior cruciate ligament. On the other hand, the periligamentous soft tissues were richly vascularized and surrounded the graft by 1 month. This is in sharp contrast to Weiler et al. [66] who performed a similar study in sheep, detecting a significant neovascularization in the first 3 months after reconstruction.

Similarities between animal and human studies show that loss of collagen organization is detectable in areas of the graft in which neovascularization had occurred. Because some primary cellular tissue from the graft source persists at least in humans due to a limited neovascularization, this may partially explain why controlled early loading and stress across the graft during rehabilitation in the first several months does not increase failure rates. Extensive research aimed at determining the optimal balance of healing and graft loading in the early phases of healing has been inconclusive. Ideal loading conditions must be low enough to maintain graft integrity and prevent stretching, laxity, and future instability while simultaneously high enough to encourage a robust, organized, and productive ingrowth and subsequent maturation of cellular and extracellular components for a successful transformation to maintain knee stability.

7.4.1.4 Ligamentization

It is thought that the ligamentization process is the result of the proliferative stage starting around the twelfth week. Throughout this phase, the reconstructed ligament builds upon the preparatory structural and mechanical adaptations it has made thus far. Throughout this final stage, the reconstructed ligament makes several fundamental and distinct adaptations to closely resemble a native ACL. Microscopically, as with a native ACL, metabolic activity of the fibroblasts begins to slow and cellular morphology resembles a more quiescent shape as growth factor and protein synthesis drops to levels of a native ACL. Microscopically this is found within the first 3 months in animal studies [55, 56, 65, 66].

Nevertheless, multiple important differences can still be seen in the structural composition. Reorganization of the collagen in structure, the collagen type, and size are noticed. Similar to the intact ACL, a more organized, fascicular network of collagen appears. The crimp pattern seen in the early and proliferative phases is partially reestablished. This crimp alteration has been observed in sheep studies even up to 2 years [56, 70]. Compared with the native ACL, the collagen size remains small in the reconstructed PT or hamstring graft as opposed to a heterogenous mix of both small and large collagen fibrils. The small collagen fibril diameter persists throughout the lifetime of the new ligament [22, 27, 45, 71]. Type III collagen content and synthesis, not normally found within the intact ACL, slows in its production and is maintained for at least 2 years [39, 72]. It is noted that in a goat study at 3 years, type III collagen returned to normal values [68].

The type and density of crosslinking of the collagen, in particular hydroxypyridium crosslink density, is an important feature in reparative tissues. With lower concentrations found in reparative tissues, mechanical performance has been shown to have a linear relationship when looking at crosslink density and Young's modulus of elasticity [68, 73]. Previously, it has been reported that newly synthesized collagen fibrils have small diameters (<100 nm) and contain type III collagen [74–76]. In early ligamentous repairs and scar tissue on the skin, type III collagen is found. This type of collagen is less stiff than type I collagen; however, as the tissue matures, the type III collagen is replaced by type I collagen. Covalent crosslinks formed between collagen are nonreducible and an important determinant of mechanical strength and biochemical stability. Without crosslinking, collagen fibrils are mechanically weakened and easily damaged [68]. Similar findings have been demonstrated in various animal models due to persistent small-diameter collagen fibrils and increased type III collagen. There are significantly inferior mechanical properties in a healing graft compared with a native ACL, even after long-term healing of up to 2 years [22, 25, 56, 66, 68, 70, 77]. Throughout the first year of this ligamentization process, it is clear that the mechanical properties of the graft improve; however, for measured biomechanical properties of failure load and stiffness, the maturing graft may only reach 50% to 60% of the native ACL in animals [22, 25, 30, 44, 53, 56, 62, 65, 66, 68, 78]. Despite the adaptive extracellular matrix structural changes that have been observed for up to 3 years, it is noted that the mechanical strength of a reconstructed ACL is never fully restored to normal.

One must be careful to make direct comparisons of animal and human studies performed on ACL reconstruction. Although many of the biological features of the ligamentization process do parallel each other between study species, there are notable differences in the speed and intensity of the graft maturation process. Perhaps due to the initial limited or partial necrosis seen in the early phase of healing, the graft strength is much less effected in the early stages of healing in humans.

Nevertheless, there are proven adaptations that do occur in the grafted tissue, although it seems that complete transformation back to an intact state is not achieved. Clinically, no final conclusions can be made regarding the mechanical strength of the healing tissue in humans due to limited techniques to measure in vivo mechanical properties or whether the ligament has undergone complete ligamentization permitting a safe RTS or high-level activity.

Other key variables certainly play a role in successful graft maturation to restore knee stability and function. Anatomic graft placement during ACL reconstruction provides the best chance for proper ligament loading characteristics and environmental stimulus to drive a favorable healing process. Variations in graft loading based on the amount of healing or time from surgery must be clearly delineated in future research to encourage structural restoration of the grafted ACL to near-intact ACL function. Additionally, final graft tensioning during the index procedure must not overconstrain the newly constructed ligament, which could potentially lead to deleterious effects on the ligament and knee function [79]. Other considerations such as host factors, postoperative rehabilitation, patient compliance, and activity level are also independent predictors of a successful long-term outcome. Good graft biology and maturation requires that the graft and fixation be strong enough not only at time zero but also during rehabilitation to maximize function and reestablish muscle strength and neuromuscular control of the limb.

From the multitude of investigational studies, one of the main takeaways despite all variables is that it takes time for biological incorporation to progress toward a native ACL state (Fig. 7.1). The tension on the final construct has been found to effect the revascularization process that must occur for successful long-term function of the ligament. Patient factors such as tobacco use and diabetes may alter the intricate angiogenic pathways needed and oxygen delivery systems. Inherit healing potential of individuals also varies based on age, genetic background, and associated chondral, meniscal, capsular, and ligamentous injuries that occur at the time of injury.

Overall, this ligamentization process is an adaptive transformation of the graft which does not lead to a complete transformation to the biological properties found in an intact ACL. It is a combination of many variables that contribute to a healthy, mature graft. These include the mechanical environment surrounding the graft from the time of implementation. Perhaps one of the most controversial and still yet to be proven questions in the literature still prevails: is it still a matter of debate whether a full restoration of the biological and mechanical properties of the intact ACL is possible or whether the process is more

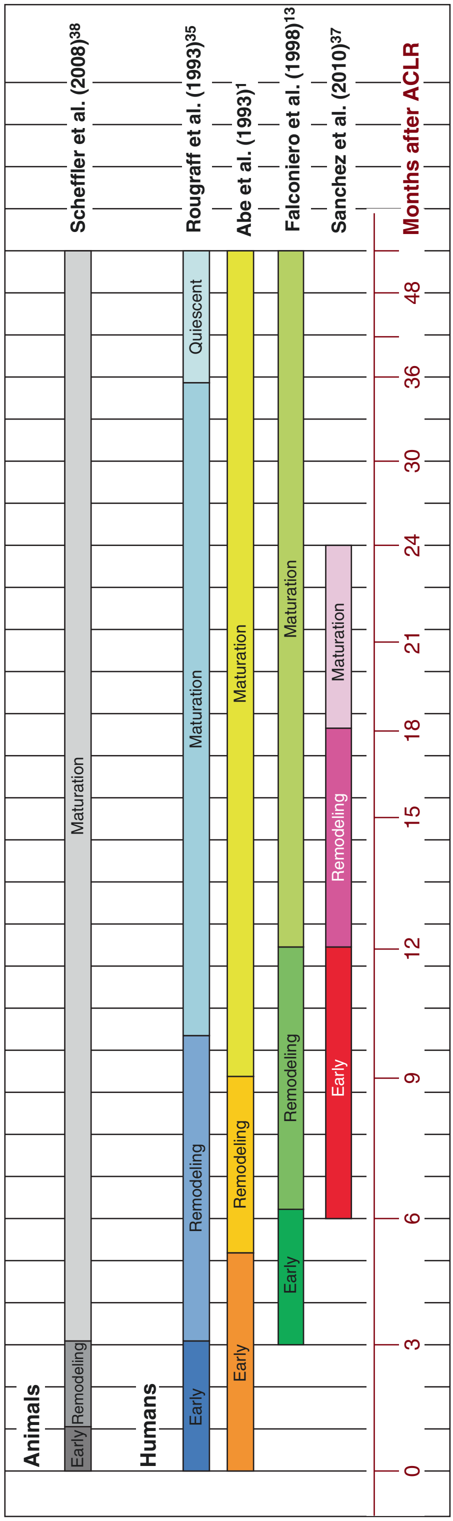


Fig. 7.1 Differing ligamentization time frames in human grafts compared with a recent review [80] of animal reports (Reprinted with permission from Claes et al. [81])

of a transformation of graft tissue that resembles but does not fully replicate the properties of the intact ACL?

7.5 Tunnel Healing

A second, equally critical step in ACL reconstruction is the necessary healing within the bone tunnels. The tunnel or socket that was created in order to pass, suspend, and fixate the new ligament graft requires sound mechanical strength, a biological process for healing, and precise anatomic placement to achieve knee stability and a successful outcome. This process is dependent on various factors including graft choice, bone quality, fixation method, tunnel size, length, mechanical stresses, and tension encountered by the graft.

Using bone-bone healing as in a bone-patellar tendon-bone (BPTB) graft, there is an advantage in terms of graft selection options for ACL reconstruction. The healing process that takes place is complex and unique which presents specific challenges. Within a bone tunnel using a PT graft, there is both a bone plug and intraosseous tendon. Due to the inherent nature of the PT graft exceeding the length of the native ACL, a significant amount of graft found in the tunnel is the tendon itself. Therefore, a healing process involves the bone-bone interface next to the plug and also the tendon-tunnel healing at the aperture of the tunnel. For successful healing, aperture healing allows remodeling to a direct type of ligamentous insertion that promotes strength [82]. The bone plug matures through a process of necrosis, resorption, and remodeling with creeping substitution [31]. At 3 weeks, Tomita et al. [31] demonstrated in BPTB grafts in beagle dogs that at the tendon-bone junction of the graft, both the noncalcified and calcified fibrocartilage layers were present. At 3 months, full incorporation with bone-bone healing occurs and it is indistinguishable from the surrounding bone.

In early healing of PT grafts in animal studies, immature granulation tissue forms between the tendon and tibial tunnel wall. Sharpey and Ellis originally described the Sharpey fibers which are implicated in indirect ligamentous insertions. These are superficial fibers that anchor soft tissue to bone through perforating superficial fibers that insert into the periosteum at acute angles. These insertions during growth are the presumptive matrix that allows the progressive mineralization of a ligament or periosteal collagen fibers [83]. Periosteum itself consists of multipotent mesodermal cells in addition to progenitor chondral and osteoid cells and, under specific conditions, forms cartilage and bone, respectively [84]. This attachment is dynamic because it allows for micromotion to occur and thus shear movements. As will be discussed later in this chapter, nonanatomically fixed grafts as seen with suspensor fixation allow for minor longitudinal movements between the graft-tunnel interface [85].

In PT grafts, in as little as 3 months and at 1 year after ACL reconstruction, biopsied tissues show the tendinous portion of the graft proximal to the bone plug healed to the tunnel wall with an indirect insertion with Sharpey-like fibers [31, 79, 86]. The healing of PT grafts in the tibial tunnel progresses from the bone plug site proximally to the tendon-tunnel junction [87]. These Sharpey fibers are composed of mainly type III collagen and mainly help to resist in shear stress.

Advantages of using a BPTB graft are the following: strength of the initial graft [88], secure fixation using interference screws [24], and biological bone-to-bone fixation [88]. However, due to the inherent nature of the length mismatch of the grafted tendon to the intraarticular length of the ACL, there is always a gap from the tunnel wall to the tendon. This mismatch may affect knee stability [89]. It has been suggested that placing a bone plug deep in the femoral tunnel is a possible risk factor for femoral tunnel enlargement [90]. Compared with the native ACL insertion site, ACL reconstructions produce a greater distance between the normal insertion site and the biomechanical point of action of the ligament [84].

The graft tendon-tunnel wall interface proximal or distal to the bone plug, on the tibia and femur, respectively, does develop postoperatively in a slower process of graft incorporation. Compared with a hamstring graft in which the cross-sectional area of the tendon in the tunnel is larger, the tendinous portion of the PT in the tunnel is significantly smaller. At 12 weeks, Tomita et al. [31] demonstrated histologically in beagle specimens using a BPTB graft that the tendon-tunnel interface fills in with dense collagen fibers that resemble Sharpey's formed from within the granulation tissue.

Healing at the specific tunnel aperture location is another critical area of healing required for successful graft maturation and long-term success. Specifically looking at this location of graft healing, Bedi et al. [91] compared intraarticular (near tunnel aperture) and extraarticular (far from tunnel aperture) fixation using suspensory graft fixation in a rat model with flexor tendon grafts (Fig. 7.2). The extraarticular fixation group at 4 weeks showed organized, fibrous matrix tissue with a narrow-tendon-bone interface. Mineral apposition rates and bone formation were also greater in this group. Osteoclastic activity was more prevalent in the intraarticular group. The intraarticular healing response was also seen to be less organized and showed less bone formation suggesting a cell-mediated role potentially leading to an impaired healing response. It was concluded that extraarticular graft fixation promoted a more robust, organized healing response at 4 weeks and that local biological and mechanical alterations related to the fixation proximity to tunnel aperture have an effect on healing.

Potential problems with graft healing may come from the less than ideal intraarticular environment in which the graft occupies. The intraarticular nature of the reconstructed graft subjects it to contact with synovial fluid which contains proteolytic MMPs. Berg et al. [82] assessed healing in a rat ACL model. After drilling both the femoral and tibial tunnels (and not implanting a graft), these investigators observed healing occurred most rapidly the further it was away from the

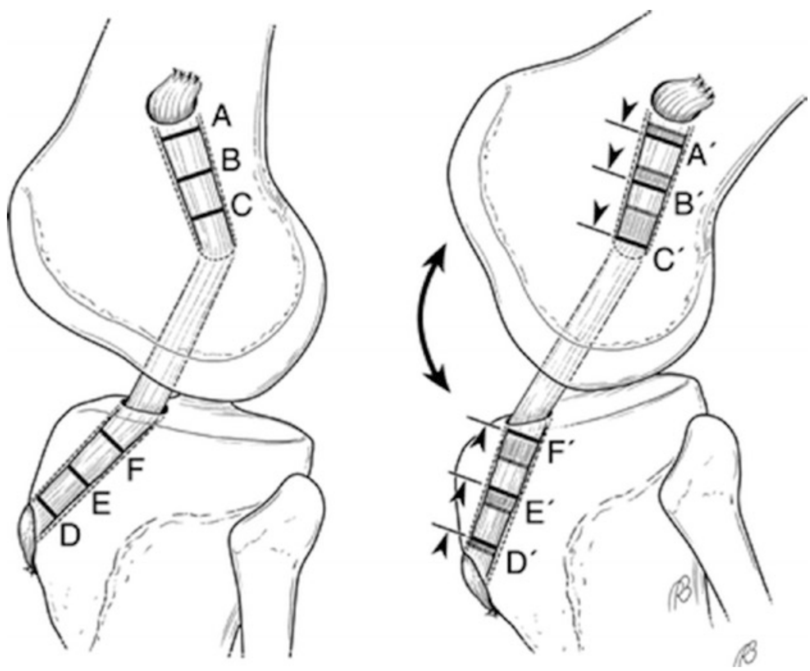


Fig. 7.2 Effect of increased distance between graft fixation points on graft-tunnel micromotion. "Suspensory fixation" at the EAA of the bone tunnels reduces construct stiffness, increases graft tunnel micromotion, and results in secondary tunnel expansion. The "bungee effect" due to longitudinal graft motion and the "windshield wiper effect" due to transverse motion of the graft in the tunnel may result in distinct differences in the mechanical environment between the IAA and EAA. Note the increased longitudinal motion of the graft at IAA (C to C′ and F to F′) compared to the EAA (A to A′ and D to D′) as the distance from the fixation points increases (Reprinted with permission from Bedi et al. [91])

joint. The slowest healing was found near the tunnel apertures, suggesting that synovial fluid infiltration may interfere with tunnel healing.

Hamstring grafts fixated with suspensory fixation heal to the tunnel wall, as vascularized granulation tissue fills in the gap at the tendon-tunnel interface. An abundance of type III collagen and inflammatory cells, mediators, and growth factors stimulate ingrowth from the periphery of the graft with Sharpey-like fibers. Shear stress is resisted from the perpendicular nature of the Sharpey-like fibers which enhances stability leading to a continuation of structural remodeling and maturation [25, 30, 43]. The collagen fiber insertional size, organization, and direction depend on strain, site, and length of insertion [92].

Stability of the attachment site with this matured granulation tissue drives chondroid cells to deposit along the length of the graft and, over time, start the process of endochondral ossification [93]. The pattern is not uniform because some regions demonstrate a cartilaginous interface between tendon and bone [84]. These regions of fibrocartilage may mature and represent a form of direct healing by enchondral bone formation [94]. It has been proposed that anatomical fixation with interference screws in a BPTB graft may promote tendon-bone incorporation via a direct healing response [95].

In most studies, a form of indirect healing between the tunnel bone and soft tissue graft is found [43]. At 3 months, biopsy specimens from hamstring tendon (HT) suspensory fixation (TransFix) showed a fibrovascular interface with few collagen fibers. From 5 to 10 months, Sharpey fiber numbers increased, and by 1 year the tendon-bone interface was seen to have a continuous layer of Sharpey-like fibers.

If a secure indirect attachment does not develop, problems within the tunnel may occur. The concept of tunnel enlargement (Fig. 7.3) found in hamstring tendon grafts is derived from this "windshield wiper" effect of the graft and synovial fluid interface [97]. Fixation techniques with suspensory fixation can produce micromotion which may impair a robust graft-tunnel healing leading to the development of a metaplastic fibrous cartilage transition [98].

Fig. 7.3 Example of tunnel enlargement requiring ACL revision reconstruction with use of staged bone grafting (Reprinted from Noyes and Barber-Westin [96])

Tendon-bone micromotion seems to have an inverse correlation between motion and healing in the femoral tunnel. Graft tunnel motion may impair early graft incorporation and may lead to osteoclast-mediated bone resorption [99, 100]. This micromotion can also be affected by the type of rehabilitation prescribed, which is discussed in further detail later in the chapter. Understanding the differences of graft healing and integration at the various tissue interfaces within the tunnels are important for postoperative rehabilitation [99].

Of importance, these histological biopsy studies are taken at the time of revision ACL reconstruction. Because tunnel-bone healing is a potential contributor to graft failure, it is possible that the biopsied tissues do not truly represent the healing process of a successful ACL reconstruction. Clinical extrapolation of this data must be used with caution. Despite attempts to recreate the native ACL attachment site with various modern reconstructive options, the ideal tendon graft cannot replicate a broad, surface attachment to the bone with an intermediate zone of fibrocartilage [84].

7.5.1 Bone Quality Composition

Fixation of graft in the tibial and femoral bone requires adequate structural support necessary to hold the graft suspended in each tunnel. It is very likely that successful graft incorporation depends on the bony environment receiving the graft [101]. The bone quality, quantity, and distribution in which this fixation occurs and its role in healing are different between the tibia and femur. The distal femoral metaphyseal tunnel is created within a densely cancellous network of bone. On the tibial side, marrow elements of the metaphyseal bone are more prominent, especially in animals such as rabbits. Insertion of a grafted tendon into each site may invoke a much different cellular response leading to different functional consequences. Similarities have been demonstrated in extraarticular healing of ligaments. Grassman et al. [101] conducted an experimental model with rabbits on extraarticular medial collateral ligament reconstruction with a free tendon graft. Tissue healing into cancellous bone was found to be superior to that of a marrow-filled space. Therefore, the bony environment of graft incorporation is a greater determinant of healing success than the actual graft choice (HT or PT) [101]. This direct anatomical extrapolation may not perfectly represent the human knee because the femur and tibia are more similar to cancellous-filled rabbit femur.

7.5.2 Graft Fixation Technique

The choice of ACL graft fixation used to secure the graft during healing must allow for early loading without slippage, elongation, or deformation of the tissue. Until healing in the tunnels has occurred at the bone-bone or tendon-bone junction, the graft is only as strong as the fixation at time zero of implantation. These considerations necessitate a delay in return to function.

Types of human fixation methods and the corresponding biomechanical and histological impact that occurs have been studied in animals at length. Interference screws in the tibial tunnel of a goat model with Achilles split autografts demonstrated healing with and without a fibrous interzone. This fibrous interzone is composed of vascularized, highly cellular fibrous tissue which over time reorganizes its matrix until Sharpey-like collagen fibers and the fibrous interzone-graft interface are indistinct. This is thought to be the earliest sign of osseous integration. At 6 weeks, in regions where the tendon was directly adjacent to the bone, there was no fibrous interzone present and osteoblastic and osteoid formation was found. However, some of the graft closest to direct bone-tendon interface did develop a fibrous interzone with Sharpey-like fibers. This was found at regions of high stresses such as the articular tunnel aperture site. This may indicate that interference fixation through a compression effect may provide a stimulus toward the development of a more physiological and direct graft insertion without the development of a fibrous interzone [62]. Weiler et al. [62] hypothesized that for the creation of a direct insertion site at the articular tunnel aperture, certain graft-tunnel forces must be neutralized, which may be accomplished with an interference screw. The effect of interference screw fixation may prevent tunnel widening and promote tendon-bone incorporation. It is unknown if this mechanism is from the neutralization of forces from the screw or synovial fluid blockage into the tunnels [62]. Other factors including screw composition and biodegradability of the screw material may also contribute to an inflammatory response at the graft anchorage site leading to possibly adverse cellular reactions [102–108]

Comparing an interference screw to spiked screw and water (WasherLoc), the biological healing response with an interference screw was observed to be slower in an experimental study of ovine tibiae. This was confirmed after the removal of the hardware at 4 weeks because the data showed the tensile strength and stiffness of the graft fixated by the interference screw were 31% and 36% of original implantation strength. In contrast, the WasherLoc fixated graft showed strength and stiffness at 50% and 143% compared to initial implantation. These findings led the authors to conclude that interference screw fixation may impair tendon healing within the osseous tunnel by decreasing the contact area with the bone and perhaps preventing the ingrowth of blood supply to the grafted tissue. Additionally, the fixation strength of the cancellous bone with an interference screw is less stiff than fixation of a graft in cortical bone with the spiked screw and washer [109]. Therefore, with various fixation methods there are different amounts of compressed tendon lengths, grip of the graft, and purchase on the quality of bone [110].

Despite initial high graft fixation strength and stiffness with a variety of implants, it is not until biological healing and maturation of the tunnel-graft interface occurs that allows for the increased demands in postoperative rehabilitation.

7.5.3 Tunnel-Tendon Gap Size

Bone-tendon healing in the osseous tunnel and the relative gaps between interfaces are other important variable in the healing response that occurs. This is encountered in double HT grafts with suspensory fixation devices. With these fixation devices, there is essentially no compressive effect imparted to the graft-tunnel surfaces. Therefore, healing tissues must bridge this gap to indirectly allow for biological ingrowth to occur. In rabbit models with semitendinosus grafts, smaller gaps led to more organized, dense healing tissue with an associated increase in tensile strength seen at 2 weeks [111]. At 6 weeks, the histological interface between tendon and bone appears more mature with a better press-fit diameter of the graft. Increasing the bone-tunnel size from 1.5 to 1.8 mm of tendon-tunnel diameter mismatch resulted in a decrease in pullout strength by roughly 25% [112]. Achieving a near press-fit of a tendon within the tunnel is an important technical consideration during reconstruction. From these studies, it is recommended that to improve anchoring strength of a grafted tendon in an osseous tunnel, the tunnel size should be approximately the same diameter of the grafted tendon [111].

7.5.4 Tunnel Length

Technical surgical factors play a role in healing of the newly reconstructed ligament. Intuitively, it would make sense that increasing the amount of graft surface area and contact within the osseous tunnel helps to improve biological incorporation. Greis et al. [112] demonstrated in a canine model that 1 cm of tendon-bone tunnel contact had approximately 60% pullout strength compared with 2 cm of tendon-bone contact at 6 weeks [112]. Conversely, Yamazaki et al. [113] demonstrated no difference in tendon grafts with 15 mm versus 5 mm of graft contact in tibial tunnels in a canine model at 6 weeks in ultimate failure load and linear stiffness. Long-term clinical results are unknown with a shortened tunnel graft and the surgical technique guidelines remain to have as much graft tunnel length as possible for added graft incorporation and overall long-term strength of the ACL reconstruction. Therefore, one can assume that the ultimate strength of the graft during the healing and maturation process is due to both the aperture healing and added intraosseous incorporation along the graft tunnel and this imparts a minimal threshold that is still unknown. The minimal amount of tendon-tunnel bone contact needed to allow for a successful outcome has not been determined.

7.5.5 Mechanical Stress and Graft Healing

The magnitude, frequency, and direction of loading have direct implications to the reconstructed ligament and the biological healing response generated. These forces experienced across the graft change with varying fixation strategies which may allow micromotion between the graft-tunnel interfaces. Additionally, a “conservative” versus “aggressive” postoperative rehabilitation protocol may alter this biological healing environment.

In aggressive rehabilitation protocols using a quadrupled hamstring graft, greater tunnel widening was present [114]. Radiographic and histological analysis of this phenomenon has demonstrated that most noticeably this was seen at the tunnel apertures and least at the end of each tunnel which is adjacent to the graft fixation. At the apertures, more fibrovascular scar tissue forms at the interface. This relationship of graft-tunnel motion and healing demonstrates an inverse healing relationship. This persistent micromotion in the face of continued stress across the graft drives cellular adaptions to have an osteoclastic predominance at the aperture site and provides evidence to support an osteoclastic-mediated bone resorption pathway leads to tunnel widening [100].

In rabbit specimens after reconstruction, immobilized groups compared with no immobilized groups showed a more organized healing response, resulting in improved mechanical strength at the bone-graft junction. The conclusion was made that failure to immobilize delayed the biological fixation process in the bone tunnel, and a certain amount of immobilization was required for proper healing [115].

Other postoperative regimens in rodents and the effect on tendon-bone healing have been explored. Rats with controlled cyclic axial loading for short periods of time each day compared with an immobilized group had greater inflammation and less bone formation in the tunnels [116]. In the same model treated with a delay in cyclical loading (4 days), improvements in mechanical properties in the healing response were noted compared with groups with immediate mobilization (1 day post-op) without immobilization and prolonged immobilization using an external fixator device to limit motion of the surgical extremity (2 weeks post-op) [117].

These studies suggest that perhaps a period of reduced activity following ACL reconstruction may be more advantageous to graft healing. This allows for an adequate biological healing response to begin, mature, and stabilize itself prior to mechanical loading. The early loading of the graft has been shown to delay and impair the quality of histological healing tissue which may alter the grafts' long-term healing potential. This can be thought of much like a healing fracture. Too much mechanical stress and strain early can be deleterious at the fracture site leading to nonunion or hardware failure. However, not enough loading leads to bone resorption and lack of biological stimulus needed to promote healing. Based on the current literature, we would not support an aggressive rehabilitation protocol because of the need for early, organized healing to promote long-term health of the grafted tissue allowing for necessary ligamentization. As of now, the literature is unclear regarding the optimal rehabilitation program that balances the need for healing and functional return.

7.5.6 Graft Tension

Graft tensioning at the time of fixation has been studied extensively in ACL reconstruction. A reconstructed ligament must have enough tension to adequately restore knee stability not only at time zero, but throughout the ligamentization process. Both under- and over-tensioning the graft are known to be deleterious to knee stability, place nonphysiological forces on the graft, overconstrain the knee, and increase contact forces on the articular cartilage [118–123]. In a goat study by Abramowitch et al. [124], grafts were fixed at low (5 N) and high (35 N) initial graft tension. At time zero, the high graft tension group showed greater joint stability by 35% compared with the low tension group at 30°, 60°, and 90° of knee flexion with regard to anterior-posterior (AP) translation. After 6 weeks, the low and high tension groups had similar loading profiles; however, neither graft tension group restored knee stability to native ACL control specimen values. The high tension group had increased AP translation of 145%, 147%, and 187% at knee flexion angles of 30°, 60°, and 90° from time zero to 6 weeks. There were no significant differences found between the low and high tension groups at 6 weeks. However, at 30° of knee flexion, the high tension group had a mean AP translation of 6.9 ± 2.7 mm, while the low tension group had a mean of 9.7 ± 1.8 mm. From time zero to 6 weeks, each tension group's cross-sectional area more than doubled in size. The authors' hypothesis was confirmed in that the graft's viscoelastic behavior and structural properties were not affected by the magnitude of initial graft tension. Limitations of the study included immediate weight-bearing of the goats within hours after the surgery which may have contributed to early graft slippage and elongation, number of specimens studied, and short time course which does not reflect the typical recovery period following ACL reconstruction in humans.

Regarding the direction of load across the bone-tendon graft site, it has been reported that healing occurs as a result of mechanical stress across the graft. In a rabbit model with extraarticular tendon grafts, it was observed that tensile stresses enhanced the healing process, compressive forces promoted chondroid tissue, and shear load had no major effect. Based on the direction of the tunnel in relation to the intraarticular axis of the tendon graft, these forces become distributed differently across the bone-tendon junction [125]. Further study to better delineate this concept with concern to graft maturation has yet to be fully elucidated.

7.6 Allograft Healing

Allograft tissue for ACL reconstruction is another commonly used graft material. Advantages for the use of allograft tissue include a lack of donor site morbidity, time of operation, and availability across institutions [126]. Alternative uses include revision ligament surgery and multiligamentous knee operations. Several concerns regarding allograft use include the variability in graft processing with radiation and chemical treatments, donor tissue quality and site, and potential for disease transmission. Furthermore, key structural and healing response differences have been identified. Multiple animal and human publications comparing autografts and allografts in ACL reconstruction demonstrate mixed results with regard to short- and long-term outcomes [127–130].

Results have not been as promising in animal studies that assessed the healing response and graft incorporation of allograft tissue. Multiple investigations have demonstrated that the rate of incorporation in the tunnels is slower and less complete. Soon after graft fixation, the mechanical strength declines as seen in autograft tissue; however, this decline is to a greater extent than autografts. Comparison of autografts to allografts at 6 months demonstrates that allografts have inferior loads to failure, smaller cross-sectional areas, and laxity to restraining joint translations [1, 21, 131–136].

A persistent inflammatory state led by the immune system produced by the allograft leads to increased graft necrosis and matrix turnover leading to the greatest initial decline in biomechanical properties of the graft when compared with autograft tissue [1, 21, 131–139]. Allograft sterilization processes attempt to prevent a robust host immunogenic response. Nonetheless, there are some persistent matrix antigens that do incite a localized immune response. This is theorized to be the reason for the variations in the biomechanical and structural properties which leads to often incomplete and prolonged healing [140, 141].

Even with a delayed progression, the phases of healing are comparable to autografts in which fibrovascular granulation tissue forms at the tendon-bone interface. Soon Sharpey-like fibers aid in anchoring the graft to the tunnel wall resisting shear stresses. As graft stability increases, bone ingrowth completes the healing process [1, 21, 131–136]. The formation of new bone happens over a period of 18 weeks to 6 months. Due to the prolonged bony healing response, this may be responsible for tunnel widening that is present during the first several weeks after surgery [22, 142].

Intraarticular ligamentization does occur and proceeds with a similar necrosis phase, host cellular replacement, and angiogenesis leading to revascularization. It has been identified in animal models that donor cellular replacement occurs as soon as 3 weeks. In humans who have undergone graft biopsies, cellular repopulation of the entire graft has only been shown to occur after 3 years, and even at 2 years the central graft remains acellular [143, 144]. Several clinical studies have reported increased failure rates of allografts compared with autografts [145–148]. It is our opinion that allografts are not indicated in athletes who desire to return to high-impact activities involving cutting, pivoting, twisting, and jumping.

7.7 Healing Challenges in ACL Reconstruction

To optimize healing of the graft, there are several important factors that surgeons have strived to overcome by modifying both the biological and biomechanical environment. Gulotta and Rodeo [149] identified the following factors:

1. Inflammation at the graft site resulting in scar tissue formation.
2. Quality of bony ingrowth and the length of time over which this occurs.
3. Motion at the graft-tunnel interface.
4. Insufficient undifferentiated progenitor cells at the bone-tendon interface.
5. Lack of coordinated signaling cascade that directs healing toward regeneration rather than scar tissue formation.

7.8 Modes of Failure Based on Point of Time.

Based on the time from surgery, it has been observed that graft failure occurs in a variety of ways. At time point zero in hamstring autografts in sheep models, failures occur at the tendon-suture junction. At 6 to 12 weeks, graft pullout from shearing of the graft from bone tunnels or a midsubstance tear occurs due to the lack of formed strength at the aperture locations. After 24 weeks, grafts typically fail in the midsubstance [150]. Kondo et al. [150] demonstrated in a sheep model using semitendinosus autograft that even at 12 weeks after reconstructions, graft necrosis (Table 7.1) and a subsequent decrease in graft strength were seen. Compared with native ACL controls at 24 weeks, grafted specimens demonstrated maximum load and stiffness that were 29% and 40% of the native ACL (Figs. 7.4 and 7.5). At 1 year, the strength improved to 47% and 73% of the native ACL. At this point, the weak link in the reconstruction is not at the for-

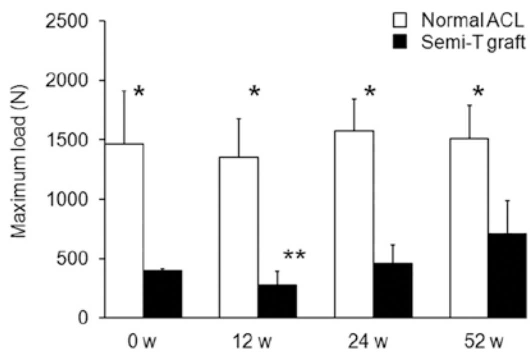


Fig. 7.4 The maximum load of the normal anterior cruciate ligaments and the semitendinosus tendon grafts. * and ** indicate results from the post hoc tests. *$P < 0.05$ compared with the semitendinosus tendon grafts in each period. **$P < 0.05$ compared with the semitendinosus tendon grafts at 52 weeks (Reprinted with permission from Kondo et al. [150])

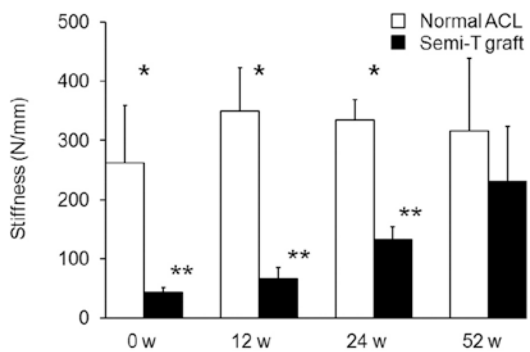


Fig. 7.5 The stiffness of the normal anterior cruciate ligaments and the semitendinosus tendon grafts. * and ** indicate results from the post hoc tests. *$P < 0.05$ compared with the semitendinosus tendon grafts in each period. ** $P < 0.05$ compared with the semitendinosus tendon grafts at 52 weeks (Reprinted with permission from Kondo et al. [150])

Table 7.1 Tissue dimensions of the ACL graft[a]

		Period (weeks)			
	Group	0	12	24	52
ACL length, mm	Graft	19.2 ± 2.0	19.5 ± 3.3	19.3 ± 1.2	19.4 ± 0.8
	Normal ACL	21.0 ± 1.1	19.8 ± 1.7	20.4 ± 2.3	19.9 ± 1.0
Cross-sectional area, mm^2	Graft	22.8 ± 4.1	30.5 ± 7.2	24.5 ± 11.5	30.4 ± 10.6
	Normal ACL	24.7 ± 5.5	24.6 ± 2.5	23.5 ± 4.0	20.9 ± 4.2

Data are expressed as mean ± standard deviation
[a]From Kondo et al. [150]

merly important fixation sites, but the graft tissue itself. The remodeling graft's mechanical properties of strength and stiffness decrease due to graft necrosis leading to loss of regular collagen type, orientation, and crimp pattern. Once the graft has progressed throughout the ligamentization process, the slow restoration of collagen and crimp properties occur.

Between 6 and 8 weeks after surgery, the bone-bone interface appears mechanically stronger than the tendon-bone interface, but this difference is not more significant by 12 weeks. These observations have led authors to conclude that soft tissue grafts such as hamstring tendons heal more slowly than PT within the bone tunnel after ACL reconstruction.

7.9 Biological Techniques of Enhancing Tendon-Bone Healing

Recently, exogenous implementation of various biological techniques has been studied and implemented to alter and improve the healing and maturation of the grafted tissue. When ACL reconstruction is performed with a HT graft, the process takes longer to provide sufficient mechanical stability at the tendon-bone interface in contrast to the PT graft [28]. Along with a slow rate of healing, the attachment site weakness of the bone-tendon may limit rehabilitation and delay return to activities [151]. One of the aims of these exogenous factors is to accelerate the normal healing response by promotion of new collagen fibers at the bone-tendon interface creating secure bony apposition. Since the site of graft fixation in the early healing phase is the weakest region of the graft, much of the postoperative rehabilitation and return to functional activity is largely dictated by the need to protect the healing of the tendon in the bone tunnels. Therefore, improving this healing response may allow for more aggressive rehabilitation and earlier return to sport than previously thought possible. Despite the theoretical advantages of using these biological techniques to alter and improve healing of the graft, it may be too early in these investigations to be able to broadly recommend and implement them in ACL surgery. Until a better understanding of these techniques along with the biological concentrations, delivery systems, and duration of effectiveness over time is delineated, surgeons must carefully decide if there is an advantage in performing these adjunctive therapies.

7.9.1 Growth Factors and Bone Proteins

Several key polypeptides such as bone morphogenic proteins (BMPs) and growth factors (GFs) which include transforming growth factors (TGFs), fibroblast growth factors (FGF), platelet-derived growth factors (PDGF), and epidermal growth factors (EGF) have been studied to ascertain what role they may have both individually and in combination in activating and regulating the proliferation of new bone and fibrous connective tissues.

Bone healing ultimately contributes to healing and biomechanical strength in ACL reconstruction [61]. Previous work has been done looking specifically at osteoinductive agents such as BMPs based on their potential to induce bone ingrowth and new bone formation [61]. BMPs initiate endochondral or intramembranous bone formation by promoting MSCs to differentiate into chondroblasts and then into osteoblasts [152]. Specifically, BMP-2 has been studied and used in spinal surgery with the potential ability to induce tendon or ligament fibroblasts to differentiate into osteoblast-like cells to augment bone-tendon healing [153–155]. Rodeo et al. [61] demonstrated in a dog model that an absorbable collagen sponge infused with rhBMP-2 resulted in increased bone ingrowth at the bone-tendon interface leading to a closer apposition of bone to the tendon. It appeared that rhBMP-2 functioned as a powerful chemoattractant for undifferentiated cells in the highly cellular granulation tissue formed between the tendon-bone interfaces. This also translated to greater pullout loads in the low-dose BMP group compared with controls at 2 weeks; however, at 4 and 8 weeks, no significant differences were found [61]. Interestingly, superior results have been found in groups treated with lower rather than higher doses of rhMBPs [156–158]. Similar findings have been found using rhBMP-7 and TGF-beta 1 in animal models [159–161].

Adjuncts with osteoconductive properties, including those with additional calcium phosphate incorporated along the tunnel-tendon interface, have shown promise in rabbit models. There was increased bone formation and statistically significant maximal tensile strength (N) in augmented groups compared with controls in specimens at 1 and 2 weeks [162]. Combating potentially osteoclastic mediated processes, as seen in tunnel widening, has been studied to see if downregulating and suppressing bone resorption could be beneficial in graft healing. In rabbit ACL reconstruction models, cellular regulatory proteins, osteoprotegerin (OPG), a known inhibitor of osteoclasts, or receptor activator of nuclear factor kB ligand (RANKL), which stimulates osteoclast formation and activity, have been investigated. In specimens treated with 100 μg OPG placed in the graft-bone tunnel interface, the amount of bone formation was significantly larger in the OPG. It is reasonable to assume that local application of OPG could support a healing process; however, further investigation on the specific dosing and drug delivery systems with extended testing times must be established. In addition, biomechanical testing was not performed, and clinical extrapolation of this data should be done with caution [163].

This potential for faster healing may have the clinical impact of preventing graft slippage. Even though graft failure at the tendon-bone interface is uncommon using HT grafts, it is possible that even subtle graft slippage could contribute to future laxity through impaired graft incorporation and resultant tunnel enlargement [164]. Limitations and effectiveness of this particular drug delivery during ACL reconstruction stem from the short half-life of growth factors in combination with synovial fluid washout leading to an alteration in therapeutic concentrations and prevention of a stout fibrin clot [161]. The optimal delivery system of these adjunctive treatments has not yet been established, although promising results from animal studies in its biological effectiveness have been shown.

7.9.2 Matrix Metalloproteinases and Tissue Inhibitors of Metalloproteinases

MMPs as discussed earlier are known to play a role in tissue healing and remodeling. They interact closely with inflammatory cytokines such as IL-1 and TNF. Synovial fluid contains metalloproteinases and, therefore, synovial fluid tracking into the osseous tunnels certainly has implications in tunnel healing. These MMPs including collagenases and stromelysins have been shown to induce a catabolic, degradative effect on connective tissues and specifically collagen [165]. Three main types of collagenase enzymes have been studied: interstitial collagenase (MMP_1), neutrophil collagenase (MMP_8), and collagenase 3 (MMP_{13}). These collagenases function to degrade triple helix regions of collagen types I, II, and III [166]. As discussed previously in the early phase of healing, these enzymes are locally released in the intraarticular space after ACL injury and subsequent reconstruction [167–169].

Hypothesizing that enzymatic degradation imparted by MMPs has an adverse tendon-bone healing effect has led to investigations looking at tissue inhibitors of metalloproteinases (TIMPs). TIMPs are proteases that act in sequence with MMPs and effectively balance the degradative and remodeling pathways of the extracellular matrix (ECM). Attempts to modulate the normal regulatory pathways between MMPs and TIMPs have been performed. In particular, Demirag et al. [166] used alpha-2-macroglobulin, an endogenous inhibitor of MMPs locally produced by macrophages and fibroblasts, to study graft healing. In a rabbit model using an intraarticular injection of α-2-macroglobulin, a nonselective collagenase inhibitor, after ACL reconstruction, there was noted to be denser, more mature fibrovascular tissue at the tendon-bone interface with a greater concentration of Sharpey fibers compared to control specimens.

Biomechanical testing yielded greater strength in those treated with α-2-macroglobulin [166]. The precise mechanism of TIMPs and their role in modulating this early inflammatory cascade with downstream influence on collagen synthesis and breakdown is still far from being completely elucidated. The significance of these findings may not be directly applicable to human and clinical use at this time; however, it does further our understanding of the complex healing cascade that occurs after ACL reconstruction. These potentially modifiable biological and mechanical components could be further selectively targeted to alter and improve the natural course of healing.

7.9.3 Cellular and Stem Cell Adjuncts

MSCs, often used interchangeably with stem cells, are pluripotent, undifferentiated cells that have significant implications in the healing process. These cells retain the innate ability to differentiate into a variety of the cellular constituents of connective tissues based upon the environment and biochemical stimulus. Current research and ongoing clinical applications of MSCs are being used to augment and drive healing and tissue regeneration. Most commonly, they are found in the bone marrow, but are also found in adipose, placental, and synovial tissues, among others. Animal research has shown that grafts augmented with MSCs have healing tissue that is more organized with greater amounts of cartilage, rather than fibrous scar tissue, at the graft interface [170].

Despite investigative work done in this evolving field of orthopedics, the accepted amounts, concentrations, and applications are still a matter of debate. The potential for MSCs in the age of regenerative medicine is being recognized as an important next step in the evolution of healing. Nonetheless, the potential to drive cellular components toward a robust, organized healing response in the face of an inflammatory sequence of events is complex and further research is necessary.

7.9.4 The Inflammatory Response

Immediately following surgical reconstruction, the cellular milieu of the knee sees a surge of inflammatory cells and cytokines. Under typical circumstances, the inflammatory cascade that occurs propagates healing, but irregulated control and an exaggerated response may lead to fibrosis and scar formation which may be detrimental to longevity of the ACL graft. Under ideal conditions in adults, this healing response would lead to regeneration of native tissue as opposed to healing by scar formation. The healing response in adults is starkly different than what has been found in fetal regenerative medicine, and now techniques attempting to modulate this healing effect are being both studied and implemented to allow for an organized and rapid healing process [171–173].

Initially due to the surgical procedure which involves osseous tunnel drilling, localized bleeding into the knee allows for the formation of a fibrin clot. A marked release of cytokines including TGF beta and PDGF allows for recruitment and activation of inflammatory cells. As seen in other healing tissues, polymorphonuclear (PMN) numbers increase throughout the first 2–4 days which are gradually followed and replaced by macrophages. These PMNs play a vital role in initiating early healing events that has important ramifications later in process of tendon-bone healing. Macrophage cells are important for cellular debridement and are the precursors for formation of the important granulation and vascularized tissue that surround the clot increase adherence to soft tissues to osseous tunnels [174]. Cytokines which initially recruited inflammatory monocytes now locally act upon these cells to increase cellular production and expression of MMPs from fibroblasts. Concurrently, these fibroblasts synthesize extracellular matrix proteins which slowly replace this granulation tissue with scar. Tissue degradation, production, and remodeling are regulated through the interactions with TIMPs which have been previously discussed [165].

The macrophage infiltration has been studied specifically looking at variations in function and subpopulations in macrophage type recruited to the injured tissue. Contributions from the production of soluble cytokines induce angiogenesis, fibroblast mitogenesis, and ECM remodeling [175–179]. In rat ACL reconstruction models, both ED1+ and ED2+ macrophages have been demonstrated and functions elucidated.

ED1+ antigen expression is found on the earliest macrophages after tissue injury. These cells are primarily phagocytic and act to remove nonviable cellular debris [180, 181]. Cellular transformation of some of these ED1+ macrophages may progress toward osteoclastic differentiation, which may contribute to early remodeling along bone tunnel edges. As seen in rat studies at later time points, cells in the grafted tissue stain positive for ED1+, indicating that these cells may help with cellular transformation of the tendon. Prior studies have suggested that macrophages can differentiate into fibroblastic phenotypes capable of synthesizing collagen [182]. For these cells to infiltrate into the grafted tissue, some graft degradation of the tendon ECM occurs by secreted IL-1 and TNF alpha acting upon MMPs and TIMPs.

ED2+ macrophages are more prevalent in the subacute period of injury and seem to differ from ED1+ cells in their origin. In contrast to ED1+ cells which originate from the bone marrow, vascular system, and synovium, ED2+ cells arise from the cells at the site of healing [180, 183]. ED2+ cells serve in the healing process as an anabolic and regenerative role after the initial PMN and ED1+ inflammatory state [180].

Other complex cellular events involving mast cells and pericytes have been identified and implicated in playing a contributing role in the early inflammatory cascade. Mast cells synthesize inflammatory cytokines and may supplement the neovascularization and tissue reorganization process [174, 184, 185]. Pericytes play a role as a possible precursor cell for bone formation and ingrowth at the tendon-bone junction [176, 186].

It has been demonstrated that macrophages, fibroblasts, and platelets are key cellular mediators of wound repair in most organisms, and healing occurs by a fibrotic scar rather than tissue regeneration. Wound healing in fetal medicine occurs by a process of "scarless" healing via minimal inflammatory response [187, 188]. Mice that have been genetically modified to lack functional macrophages and neutrophils heal skin wounds without scar [189]. The understanding of the biochemical role of macrophages and other inflammatory cells play during ACL reconstruction is critical; therefore, it is hypothesized that by limiting or modifying the typical adaptive responses, the specific genes for tissue expression and organization can be allowed to proceed uninterrupted to restore a histologically native tendon attachment site [174]. Other investigations into improving healing in ACL reconstruction have been performed with the idea of creating "scarless" healing. In a rat model, Hays et al. [41] used liposomal clodronate to deplete macrophages following ACL reconstruction. At all points in time when compared with a control group, the macrophage-depleted rats demonstrated narrower fibrous tissue interface, accelerated healing, and maturation of collagen fibers. At 42 days, in the macrophage-depleted group versus the control groups, a greater mean load to failure (13.5 ± 4.2 N and 9.7 ± 3.9 N) and mean stiffness (11.5 ± 5.0 N/mm and 7.5 ± 3.2 N/mm) were reported. By suppressing the early "destructive" phase of healing by macrophage and TGF-beta suppression, it is possible to allow for the expression of more beneficial regenerative healing pathways rather than scar formation.

Suppression of the early inflammatory response using selective cyclooxygenase 2 (COX) inhibitors such as indomethacin and celecoxib in rotator cuff rat models has not shown promising results. Compared with controls, the treated group showed inferior histological and biomechanical responses [190].

These biological processes governing healing are complex and far from being completely understood. However, it does appear that through targeting specific cellular and inflammatory mediators, significant alterations to the healing process can be made. Selectively altering the cytokine, growth factors, and hormones is a future target in the challenge of improving tendon-bone remodeling in ACL reconstruction.

7.10 Assessing Graft Maturation and Healing through Imaging

Attempting to determine when a patient or athlete is ready to return to activities requires a team approach. Clinical examination findings through Lachman, KT-2000 testing, effusion, range of motion, strength, and neuromuscular control must be confirmed and documented. A structured and unique rehabilitation protocol specific to the graft choice and patient demands must have been met. Return to play protocols and programs are critical to long-term protection of the graft and prevention of future injuries. After rehabilitation parameters are met and the patient is "ready to play," how do we know with confidence the graft healing is complete? Or has it healed enough? Has the ligamentization effectively transferred the necessary biological, mechanical, and structural properties to be able to withstand the physical demands placed on upon it? The interest generated by these questions stem from physicians and team doctors attempting to provide a patient with the most complete risk profile, with the strategy to prevent graft failure. Currently, the types of imaging modalities used in assessing graft maturation are not well understood. There is no current surgeon consensus recommendation that can be made for or against the use of imaging studies that determine if the ligamentization process is complete. Modalities such as plain radiographs, computed tomography (CT), and MRI provide a noninvasive assessment of the graft. Advanced imaging techniques have gained considerable interest and are being developed to indicate the maturation status of the graft which helps to provide an individualized rehabilitation.

7.10.1 Radiographs

Valuable clues are garnered from standard anteroposterior and lateral radiographs. The position of tunnels, fixation devices, and graft incorporation can be visualized [191–193]. Due to delayed incorporation and laxity, tunnel widening can be seen [191, 194–196]. Subtle findings such as a cortical rim can be visualized. This has been shown histologically to correlate with graft incorporation [195, 196]. Although cheap and accessible with limited radiation risk to the patient, radiographs may not provide the necessary detail that CT and MRI offer.

7.10.2 Computed Tomography

Improved detail of tunnel position is one of the advantages of using CT. Bony landmarks including the lateral intercondylar ridge that has been defined on the medial wall of the lateral femoral condyle help locate the anatomical origin of the ACL [197]. In animal models with both soft tissue and osseous grafts, the cortical rim and cross-sectional area of the tunnels have been used to assess healing [194, 195].

7.10.3 Magnetic Resonance Imaging

MRI is another noninvasive imaging test that can provide impactful information in the postoperative setting of ACL reconstruction. Data regarding the native anatomy, tunnel locations, tunnel width, graft integrity, volume, composition, donor site, hardware integrity, and even biomechanical parameters can be extrapolated from various MRI sequences and mapping techniques.

Detail of the osseous and vascular supply of the graft can be identified with MRI. Improved accuracy using cross-sectional imaging gives detail on the tunnel diameters, which has been shown to decrease as osseous integration and vascularity increases [193]. As described previously, MRI changes at various time points of healing have been shown to follow a stepwise progression [198]. The entirety of the graft in the femoral and tibial tunnels, as well as the intraarticular portion of the graft, can be better evaluated using MRI. The sequence of maturation occurs most rapidly in the intraarticular portion of the graft, while tunnel aperture site healing lags behind [199].

Variations in the type of MRI are used to evaluate the healing process through the vascularity of the graft. Contrast-enhanced MRI imaging during the healing process after 2 years of follow-up has been performed. During the healing process, the amount of revascularization completion coincides with the homogenously low signal intensity of the graft, closely resembling the native PCL [69]. As previously mentioned, the ACL graft revascularizes, with the most active amount of revasualization occurring at 6 to 8 weeks. This time period coincides with the worst biomechanical parameters of the graft in the process of ligamentization as neovascularity penetrates from the periphery of the graft centrally at about 3 months from surgery. The periligamentous tissues of BPTB grafts in the remodeling phase are vascularized and have been found to correlate with increases in MRI signals after 16–18 months, similar to a native ACL signal [200–202].

MRI signal intensity can be altered by unrelated factors such as the image acquisition techniques and scanner characteristics. Even graft impingement from intercondylar notch contact on the graft has been shown to be a cause of signal alterations [203].

MRI T2 mapping has been studied using T2 relaxation times which have been shown to be affected by the collagen, proteoglycan, and water content [204, 205]. Fleming et al. [206] showed that 6 weeks following ACL PT reconstruction in goats a correlation between volumetric measures of the graft (graft volume) and structural properties with regard to linear stiffness and AP laxity.

Hardware implanted during ACL reconstruction and its relative location and integrity can readily be visualized using MRI [207]. Bioabsorbable materials may create a host-mediate foreign body reaction leading to inflammation and even granuloma [208]. Varying compositions of bioabsorbable materials have shown varying resorption rate incorporation differences. Poly-L-lactide (PLLA) or hydroxyapatite-PLLA may take 4 years to degrade [207]. In contrast, poly-D-lactide (PDLLA) screws may be easily viewed around 6–8 months, but begin to fragment and produce extracellular matrix ingrowth at 12–16 months. Complete absorption has been found after 22 months [209]. Unlike bioabsorbable interference screws, metallic materials may produce artifact during evaluation of the postoperative graft. Techniques have been implemented to manage and reduce artifact scatter, such as decreasing slice thickness and short tau inversion recovery (STIR) sequences [210].

Scoring systems such as the Figueroa score (Table 7.2) have been developed with the use of MRI to help with determination of graft maturation status [211]. Longer echo times make it difficult to pick up signal in the tendon [212]. In attempts to enhance image quality, contrast-enhanced MRI studies have been studied. Ntoulia et al. [199] used this imaging modality to assess the intraarticular, osseous tunnels and tissue adjacent to fixation locations in the graft. Imaging was performed at 3 days and 6 and 12 months postoperatively. Contrast-enhanced MRI findings were also correlated with clinical exam findings (Lachman and pivot shift tests). PT autografts in 32 males who resumed preinjury activity levels by 1 year were evaluated. These investigators demonstrated that the intraarticular site was the fastest to show uptake of contrast at 6 months. At 12 months, the intraarticular and osseous tunnels had progression of healing at a slower pace which was still not complete. Their conclusions revealed that composition differences along the course of the graft are manifested in the revascularization process.

Ultrashort echo time (UTE) MRI techniques improve the image quality at the graft-fixation

Table 7.2 Figueroa score[a]

Item	Points
Integration: Synovial fluid at tunnel-graft interface	
Positive	1
Negative	2
Ligamentization: Graft signal pattern (> 50%)	
Hypointense	3
Isointense	2
Hyperintense	1
Characterization of graft	
Poor	2
Adequate	3–5

The Figueroa score is based on the sum of the points achieved in the two items: 2 points represents an insufficiently mature graft, while a score between 3 and 5 points represents a good ligamentization process and graft integration.

[a]From Grassi et al. [211]

interface through the visualization of short T2 components in soft tissues [206, 212–219]. UTI MRI was used 3–8 years from surgery in a group of asymptomatic men who underwent HT autograft reconstruction. High graft signal was found throughout the grafts, allowing for the capability to assess the homogeneity of the internal structure of the tendon. Fixation hardware was clearly depicted. UTE MRI may provide clinicians with valuable information of graft status after reconstructive procedures despite adjacent implants with excellent graft/implant contrast and low metal artifact [212].

UTE MRI modifications allowing high-resolution 3D images have been developed. In a porcine model using ligament volume and T_2 mapping, Biercevicz et al. [214] were able to predict the linear stiffness, yield load, and maximum load after 1 year postoperatively. This T2 relaxation time represents a parameter that could be applied universally to scanners of the same magnet strength. The ability for MRI to predict the structural properties of the graft should be the aim of future study [214].

Diffusion tensor imaging (DTI), based on MRI, is another tool that has been investigated to quantitatively evaluate ACL grafts. The origins of this type of imaging modality monitor the random movement of water molecules and help to reveal the microstructure of tissues [220]. The main application for DTI has been for reporting on white matter fibers and peripheral nerves [221, 222]. A study on the use of DTI compared with standard MRI in adults with normal ACLs has been performed [223]. Conclusions from this work demonstrated that it may provide much more profound information regarding the orientation and connections of the ACL. From the work of Yang et al. [224], DTI has been used to assess ACL grafts at variable time periods postoperatively (5 months to 10 years). These investigators found that quantitative assessment of the ACL could be performed through fractional anisotropy (FA) and apparent diffusion coefficient (ADC) that allowed for improved visualization of the graft, individual bundles, and fiber tracts. The potential use of this imaging to improve visualization and provide clinical information about ACL graft healing is only in its infancy, and further study is needed to fully understand its value and implementation.

Noninvasive imaging modalities assessing graft healing allow for more detailed information about the status of the maturity of the graft. This could potentially lead to alterations in the rehabilitation protocol or even delay return to sport if there is concern about the graft viability. In some institutions, a return to play clearance postoperative MRI has even become a part of the objective return to play criteria [203, 225]; however, there is the problem that the assessment of MRIs is still qualitative without well-defined objective criteria to assess graft maturation and clearly show the graft is “cleared for sport.” These tools require further study to better delineate the stages of healing based on MRI and correlate them with physical exam and objective clinical findings. Specialized modalities such as UTE and DTI MRI seem to have advantages over traditional MRI to assess for healing and provide incredible detail. Despite the additional detailed information these techniques provide, they are not validated or are universally available.

7.11 Future Directions of ACL Healing: ACL Preservation and Bioenhanced Repair

Despite vast improvements in our knowledge of ACL injuries and refinements in surgical techniques, there remains an unacceptably high rate of failure [226–228]. A variety of injury patterns based on the location of the ACL injury have been described. Classification systems have been developed to localize the specific location of injury, which could have implications for treatment with newly developed ACL preservation techniques [229–231]. This has led to the development of ACL preservation techniques with the idea of facilitating healing of the ligament, rather than replacing it. ACL preservation is once again regaining interest with a better understanding of ACL injury patterns, improvements in quality of tissue engineering techniques, minimally invasive arthroscopic techniques, and advances in suture anchor and fixation methods [14].

7.11.1 Bridge-Enhanced Anterior Cruciate Ligament Repair

Techniques have been described as a means to bridge the gap between torn ends of the ACL which provides a scaffold of tissue. Bridge-enhanced ACL repair (BEAR) technique uses a biological bovine scaffold to fill the space, providing an environment for cellular repolarization, revascularization, and remodeling. Historically, high rates of failure in primary ACL repair are likely due to the loss of a stable blood clot due to fibrinolytic enzymes typically found in the synovial environment [13]. Studies assessing primary ACL repair with and without a scaffold and augmenting the repair with or without platelet-rich-plasma (PRP) have demonstrated that using both a collagen scaffold and PRP in combination significantly improves healing over traditional suture repair. Comparing ACL reconstruction versus bioenhanced repair in skeletally immature pigs, Vavken et al. [232] demonstrated that the structural properties of the bioenhanced ACL were not significantly different from ACL reconstructed grafts. If equivalent efficacy could be shown comparing ACL bioenhanced repair and ACL reconstruction in humans, there would be several advantages. First, no harvest of donor tissue would be necessary and the procedure would be less invasive and painful and would promote a faster recovery. Native anatomical features of direct, anatomical ligamentous attachment sites and maintained proprioceptive function would be restored promoting normal knee kinematics and potentially decreased risk of developing osteoarthritis. Additionally, pediatric patients with ACL injuries could be treated without concern for physeal injury [233–236].

This technique of bioenhanced ACL repair has shown promise; however, refined and reproducible repair techniques must be established. Some authors are using this technique for the common ACL midsubstance ruptures; however, a more optimal choice for this repair pattern are proximal ACL tears close to or directly at the femoral attachment site [229, 236]. The optimal scaffold and biologic combination to augment this repair have yet to be clearly defined and more research is needed in this fascinating, potentially transformational treatment.

7.11.2 Arthroscopic Primary ACL Repair with Suture Augmentation

Greater emphasis has been placed recently on the precise location of ACL tear which may allow for repair of ACL. The reattachment of the proximal tear avulsion to the femoral wall seems to lend itself most favorably to repair and reattachment with significant healing capacity [237, 238]. Proximal tears with good-quality tissue treated with arthroscopic primary repair with suture anchors have shown acceptable outcomes at short- and midterm follow-up at 2 and 5 years with regard to knee stability, patient reported outcomes, and return to activity levels [14]. Due to lack of tissue quality and inability of proximal reattachment, only a small percentage of patients, 11 of 144 tears (7.6%), were indicated for proximal tear repair [14]. MRI studies that examined specific locations of ACL tearing patterns have demonstrated that only 16% of patients had these type 1 tears, located in the most proximal 10% of the ligament [231]. It appears that with improved patient selection through a minimally invasive arthroscopic approach, good results have been demonstrated with this treatment. Other advantages include the lack of potential for complications regarding donor site morbidity, less pain, improved range of motion during early rehabilitation, and the ability to perform a reconstructive type procedure if failure does occur [14]. Compared with ACL reconstruction, primary ACL repair of proximal tear patterns has demonstrated comparable knee stability in Lachman, pivot shift testing, and KT-1000 measurements. IKDC scores were not statically different between groups postoperatively [14]. Long-term outcomes and randomized controlled trials are needed to ascertain the exact role for this treatment of ACL injury and for treatment algorithms to evolve. Nonetheless, the opportunity to preserve the native ligament when possible to reestablish knee stability and promote healing through improved surgical techniques should be in the ever-growing armamentarium arthroscopic surgeons can offer their patients.

7.11.3 Dynamic Intraligamentary Stabilization

Dynamic intraligamentary stabilization (DIS) is a reparative technique that involves the insertion of a threaded sleeve with preloaded spring from the anteromedial side of the tibia. Suture is passed through the middle of the torn ACL and secured with a cortical button the femur [239]. At 1-year follow-up, there was satisfactory functional recovery and low reinjury rates [240]. This form of treatment has shown promising results with and without biological augments [241, 242]. This technique appears to allow for close approximation of the two ends of the ACL creating an ideal healing response while knee stability is maintained [239, 243]. Studies performed to date have been case series mainly, and further investigation with long-term results and in controlled trials is needed.

In summary, it may be possible to preserve the ACL and promote primary healing through the aforementioned techniques. Strict patient selection and early intervention are imperative to a successful outcome if performing these procedures. Clear advantages of maintaining native insertion sites, less donor site morbidity, and earlier rehabilitation are evident. Despite the encouraging results of clinical studies performed with DIS, these studies have been performed in the hands of select researchers at the same medical center. Therefore, the authors agree that further clinical research is required at independent locations in well-designed, controlled studies in animal, cadaveric, and human models prior to the universal implementation of these techniques [244]. This once historical treatment option is making a resurgence in attempts to improve patient outcomes and improve function, but its utility at this time has yet to be established.

7.12 Conclusion

The understanding of the complex healing process of the reconstructed ACL is evolving. This process more commonly known as ligamentization should be considered more than a theory based on the extensive research that has been conducted showing there are indeed structural changes in the microscopic and macroscopic architecture of the ligament as it matures with time. Not just limited to the intraarticular component to the graft, complex healing responses occur along specific points of the graft-host interface, each of which is unique. Attempting to control for various patient factors, surgical techniques, graft selection, graft positioning, tensioning, and rehabilitation protocols all combine to lead to a successful outcome. Timing of allowing patients to return to activity and sport is controversial; however, through sound surgical techniques, a multidisciplinary team approach, completion of established clinical and functional rehabilitation protocols, and advanced imaging modalities, it may be considered prudent to provide a patient evidence of the status of the graft maturation prior to delivering them back to activities that would otherwise place an immature graft at risk for reinjury. Augmenting reconstructions with targeted biological responses may promote the human healing response. Ligament preservation through primary repair of a torn ACL has a growing interest in the literature with potentially a transformational clinical impact. With a growing body of research and scientific understanding of the healing response, healthcare providers are equipped to harness, promote, and protect a robust and organized healing response and should be able to guide patients with clear understanding and knowledge of ACL healing to produce the greatest clinical outcome.

References

1. Arnoczky SP, Tarvin GB, Marshall JL. Anterior cruciate ligament replacement using patellar tendon. An evaluation of graft revascularization in the dog. J Bone Joint Surg Am. 1982;64(2):217–24.
2. Relph N, Herrington L, Tyson S. The effects of ACL injury on knee proprioception: a meta-analysis. Physiotherapy. 2014;100(3):187–95. https://doi.org/10.1016/j.physio.2013.11.002.
3. Fujioka H, Thakur R, Wang GJ, Mizuno K, Balian G, Hurwitz SR. Comparison of surgically attached and non-attached repair of the rat Achilles tendon-bone interface. Cellular organization and type X collagen expression. Connect Tissue Res. 1998;37(3–4):205–18.
4. Niyibizi C, Sagarrigo Visconti C, Gibson G, Kavalkovich K. Identification and immunolocalization of type X collagen at the ligament-bone interface. Biochem Biophys Res Commun. 1996;222(2):584–9.
5. Sagarriga H, Visconti C, Kavalkovich K, Wu J, Niyibizi C. Biochemical analysis of collagens at the ligament-bone interface reveals presence of cartilage-specific collagens. Arch Biochem Biophys. 1996;328(1):135–42.
6. Butler DL, Grood ES, Noyes FR, Zernicke RF. Biomechanics of ligaments and tendons. Exerc Sport Sci Rev. 1978;6:125–81.
7. Perrone GS, Proffen BL, Kiapour AM, Sieker JT, Fleming BC, Murray MM. Bench-to-bedside: bridge-enhanced anterior cruciate ligament repair. J Orthop Res. 2017;35(12):2606–12. https://doi.org/10.1002/jor.23632.
8. Murray MM, Martin SD, Martin TL, Spector M. Histological changes in the human anterior cruciate ligament after rupture. J Bone Joint Surg Am. 2000;82-A(10):1387–97.
9. Feagin JA Jr, Curl WW. Isolated tear of the anterior cruciate ligament: 5-year followup study. Clin Orthop Relat Res. 1996;325:4–9.
10. Marshall JL, Warren RF, Wickiewicz TL. Primary surgical treatment of anterior cruciate ligament lesions. Am J Sports Med. 1982;10(2):103–7.
11. Tyler TF, McHugh MP, Gleim GW, Nicholas SJ. Association of KT-1000 measurements with clinical tests of knee stability 1 year following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 1999;29(9):540–5. https://doi.org/10.2519/jospt.1999.29.9.540.
12. Strand T, Molster A, Hordvik M, Krukhaug Y. Long-term follow-up after primary repair of the anterior cruciate ligament: clinical and radiological evaluation 15–23 years postoperatively. Arch Orthop Trauma Surg. 2005;125(4):217–21. https://doi.org/10.1007/s00402-004-0766-2.
13. Vavken P, Murray MM. The potential for primary repair of the ACL. Sports Med Arthrosc Rev. 2011;19(1):44–9. https://doi.org/10.1097/JSA.0b013e3182095e5d.
14. DiFelice GS, van der List JP. Clinical outcomes of arthroscopic primary repair of proximal anterior cruciate ligament tears are maintained at mid-term follow-up. Arthroscopy. 2018;34(4):1085–93. https://doi.org/10.1016/j.arthro.2017.10.028.
15. Alm A, Stromberg B. Transposed medial third of patellar ligament in reconstruction of the anterior cruciate ligament. A surgical and morphologic study in dogs. Acta Chir Scand Suppl. 1974;445:37–49.
16. Amiel D, Frank C, Harwood F, Fronek J, Akeson W. Tendons and ligaments: a morphological and biochemical comparison. J Orthop Res. 1984;1(3):257–65. https://doi.org/10.1002/jor.1100010305.
17. Kirschner S. Wilhelm Roux's concept of'developmental mechanics. Wurzburger medizinhistorische Mitteilungen. 2003;22:67–80.
18. Roux W. Die Entwicklungsmechanik, ein neuer Zweig der biologischen Wissenschaft 1904. In: Von der Naturforschung zur Naturwissenschaft: Springer; 1987. p. 265–86.
19. Cooper DE, Deng XH, Burstein AL, Warren RF. The strength of the central third patellar tendon graft. A biomechanical study. Am J Sports Med. 1993;21(6):818–24.
20. Hamner DL, Brown CH, Steiner ME, Hecker AT, Hayes WC. Hamstring tendon grafts for reconstruction of the anterior cruciate ligament: biomechanical evaluation of the use of multiple strands and tensioning techniques. J Bone Joint Surg. 1999;81A:549–57.
21. Arnoczky SP, Warren RF, Ashlock MA. Replacement of the anterior cruciate ligament using a patellar tendon allograft. An experimental study. J Bone Joint Surg. 1986;68A(3):376–85.
22. Jackson DW, Grood ES, Goldstein JD, Rosen MA, Kurzweil PR, Cummings JF, Simon TM. A comparison of patellar tendon autograft and allograft used for anterior cruciate ligament reconstruction in the goat model. Am J Sports Med. 1993;21(2):176–85.
23. Kleiner JB, Amiel D, Roux RD, Akeson WH. Origin of replacement cells for the anterior cruciate ligament autograft. J Orthop Res. 1986;4(4):466–74.
24. Kurosaka M, Yoshiya S, Andrish JT. A biomechanical comparison of different surgical techniques of graft fixation in anterior cruciate ligament reconstruction. Am J Sports Med. 1987;15(3):225–9.
25. Goradia VK, Rochat MC, Grana WA, Rohrer MD, Prasad HS. Tendon-to-bone healing of a semitendinosus tendon autograft used for ACL reconstruction in a sheep model. Am J Knee Surg. 2000;13(3):143–51.
26. Liu SH, Panossian V, al-Shaikh R, Tomin E, Shepherd E, Finerman GA, Lane JM. Morphology and matrix composition during early tendon to bone healing. Clin Orthop Relat Res. 1997;339:253–60.
27. Liu SH, Yang RS, al-Shaikh R, Lane JM. Collagen in tendon, ligament, and bone healing. A current review. Clin Orthop Relat Res. 1995;(318):265–78.

28. Rodeo SA, Arnoczky SP, Torzilli PA, Hidaka C, Warren RF. Tendon-healing in a bone tunnel. A biomechanical and histological study in the dog. J Bone Joint Surg Am. 1993;75(12):1795–803.
29. Weiler A, Hoffmann RF, Bail HJ, Rehm O, Sudkamp NP. Tendon healing in a bone tunnel. Part II: Histologic analysis after biodegradable interference fit fixation in a model of anterior cruciate ligament reconstruction in sheep. Arthroscopy. 2002;18(2):124–35.
30. Blickenstaff KR, Grana WA, Egle D. Analysis of a semitendinosus autograft in a rabbit model. Am J Sports Med. 1997;25(4):554–9.
31. Tomita F, Yasuda K, Mikami S, Sakai T, Yamazaki S, Tohyama H. Comparisons of intraosseous graft healing between the doubled flexor tendon graft and the bone-patellar tendon-bone graft in anterior cruciate ligament reconstruction. Arthroscopy. 2001;17(5):461–76. https://doi.org/10.1053/jars.2001.24059.
32. Kobayashi M, Watanabe N, Oshima Y, Kajikawa Y, Kawata M, Kubo T. The fate of host and graft cells in early healing of bone tunnel after tendon graft. Am J Sports Med. 2005;33(12):1892–7. https://doi.org/10.1177/0363546505277140.
33. Cameron M, Buchgraber A, Passler H, Vogt M, Thonar E, Fu F, Evans CH. The natural history of the anterior cruciate ligament-deficient knee. Changes in synovial fluid cytokine and keratan sulfate concentrations. Am J Sports Med. 1997;25(6):751–62.
34. Higuchi H, Shirakura K, Kimura M, Terauchi M, Shinozaki T, Watanabe H, Takagishi K. Changes in biochemical parameters after anterior cruciate ligament injury. Int Orthop. 2006;30(1):43–7. https://doi.org/10.1007/s00264-005-0023-5.
35. Kleiner JB, Amiel D, Harwood FL, Akeson WH. Early histologic, metabolic, and vascular assessment of anterior cruciate ligament autografts. J Orthop Res. 1989;7(2):235–42. https://doi.org/10.1002/jor.1100070211.
36. Shino K, Horibe S. Experimental ligament reconstruction by allogeneic tendon graft in a canine model. Acta Orthop Belg. 1991;57(Suppl 2):44–53.
37. Yoshikawa T, Tohyama H, Katsura T, Kondo E, Enomoto H, Matsumoto H, Toyama Y, Yasuda K. Local administration of VEGF enhances mechanical deterioration of the tendon grafted to reconstruct the ACL, although it accelerates angionesis and cellularity and infiltration: a sheep model study. In: Paper presented at the Transactions of the Orthopedic Research. Washington DC; 2005.
38. Bosch U, Kasperczyk WJ, Oestern HJ, Tscherne H. The patellar tendon graft for PCL reconstruction. Morphological aspects in a sheep model. Acta Orthop Belg. 1994;60(Suppl 1):57–61.
39. Bosch U, Decker B, Kasperczyk W, Nerlich A, Oestern H-J, Tscherne H. The relationship of mechanical properties to morphology in patellar tendon autografts after posterior cruciate ligament replacement in sheep. J Biomech. 1992;25(8):821–30.
40. Steiner ME, Murray MM, Rodeo SA. Strategies to improve anterior cruciate ligament healing and graft placement. Am J Sports Med. 2008;36(1):176–89. https://doi.org/10.1177/0363546507311690.
41. Hays PL, Kawamura S, Deng XH, Dagher E, Mithoefer K, Ying L, Rodeo SA. The role of macrophages in early healing of a tendon graft in a bone tunnel. J Bone Joint Surg Am. 2008;90(3):565–79. https://doi.org/10.2106/JBJS.F.00531.
42. Warden SJ, Metcalf BR, Kiss ZS, Cook JL, Purdam CR, Bennell KL, Crossley KM. Low-intensity pulsed ultrasound for chronic patellar tendinopathy: a randomized, double-blind, placebo-controlled trial. Rheumatology (Oxford). 2008;47(4):467–71. https://doi.org/10.1093/rheumatology/kem384.
43. Grana WA, Egle DM, Mahnken R, Goodhart CW. An analysis of autograft fixation after anterior cruciate ligament reconstruction in a rabbit model. Am J Sports Med. 1994;22(3):344–51.
44. Papageorgiou CD, Ma CB, Abramowitch SD, Clineff TD, Woo SL. A multidisciplinary study of the healing of an intraarticular anterior cruciate ligament graft in a goat model. Am J Sports Med. 2001;29(5):620–6.
45. Weiler A, Forster C, Hunt P, Falk R, Jung T, Unterhauser FN, Bergmann V, Schmidmaier G, Haas NP. The influence of locally applied platelet-derived growth factor-BB on free tendon graft remodeling after anterior cruciate ligament reconstruction. Am J Sports Med. 2004;32(4):881–91. https://doi.org/10.1177/0363546503261711.
46. Ohno K, Yasuda K, Yamamoto N, Kaneda K, Hayashi K. Effects of complete stress-shielding on the mechanical properties and histology of in situ frozen patellar tendon. J Orthop Res. 1993;11(4):592–602.
47. Majima T, Yasuda K, Yamamoto N, Kaneda K, Hayashi K. Deterioration of mechanical properties of the autograft in controlled stress-shielded augmentation procedures. An experimental study with rabbit patellar tendon. Am J Sports Med. 1994;22(6):821–9. https://doi.org/10.1177/036354659402200614.
48. Majima T, Yasuda K, Tsuchida T, Tanaka K, Miyakawa K, Minami A, Hayashi K. Stress shielding of patellar tendon: effect on small-diameter collagen fibrils in a rabbit model. J Orthop Sci. 2003;8(6):836–41. https://doi.org/10.1007/s00776-003-0707-x.
49. Flint MH, Craig AS, Reilly HC, Gillard GC, Parry DA. Collagen fibril diameters and glycosaminoglycan content of skins--indices of tissue maturity and function. Connect Tissue Res. 1984;13(1):69–81.
50. Parry DA, Barnes GR, Craig AS. A comparison of the size distribution of collagen fibrils in connective tissues as a function of age and a possible relation between fibril size distribution and mechanical properties. Proc R Soc Lond B Biol Sci. 1978;203(1152):305–21. https://doi.org/10.1098/rspb.1978.0107.
51. Rougraff BT, Shelbourne KD. Early histologic appearance of human patellar tendon autografts used

for anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 1999;7(1):9–14.
52. Johnson LL. The outcome of a free autogenous semitendinosus tendon graft in human anterior cruciate reconstructive surgery: a histological study. Arthroscopy. 1993;9(2):131–42.
53. Ballock RT, Woo SL-Y, Lyon RM, Hollis JM, Akeson WH. Use of patellar tendon autograft for anterior cruciate ligament reconstruction in the rabbit: a long-term histologic and biomechanical study. J Orthop Res. 1989;7:474–85.
54. Shino K, Kawasaki T, Hirose H, Gotoh I, Inoue M, Ono K. Replacement of the anterior cruciate ligament by an allogeneic tendon graft. An experimental study in the dog. J Bone Joint Surg. 1984;66B(5):672–81.
55. Unterhauser FN, Bail HJ, Hoher J, Haas NP, Weiler A. Endoligamentous revascularization of an anterior cruciate ligament graft. Clin Orthop Relat Res. 2003;414:276–88.
56. Scheffler S, Dustmann M, Gangey I, Schulz T, Unterhauser F, Weiler A. The biological healing and restoration of the mechanical properties of free soft-tissue allografts lag behind autologous ACL reconstruction in the sheep model. In: Paper presented at the Transactions of the Orthopedic Research. Washington DC; 2005.
57. Kuroda R, Kurosaka M, Yoshiya S, Mizuno K. Localization of growth factors in the reconstructed anterior cruciate ligament: immunohistological study in dogs. Knee Surg Sports Traumatol Arthrosc. 2000;8(2):120–6. https://doi.org/10.1007/s001670050198.
58. Tsuchida T, Yasuda K, Kaneda K, Hayashi K, Yamamoto N, Miyakawa K, Tanaka K. Effects of in situ freezing and stress-shielding on the ultrastructure of rabbit patellar tendons. J Orthop Res. 1997;15(6):904–10. https://doi.org/10.1002/jor.1100150617.
59. Jackson JR, Minton JA, Ho ML, Wei N, Winkler JD. Expression of vascular endothelial growth factor in synovial fibroblasts is induced by hypoxia and interleukin 1beta. J Rheumatol. 1997;24(7):1253–9.
60. Petersen W, Unterhauser F, Pufe T, Zantop T, Sudkamp NP, Weiler A. The angiogenic peptide vascular endothelial growth factor (VEGF) is expressed during the remodeling of free tendon grafts in sheep. Arch Orthop Trauma Surg. 2003;123(4):168–74. https://doi.org/10.1007/s00402-002-0462-z.
61. Rodeo SA, Suzuki K, Deng XH, Wozney J, Warren RF. Use of recombinant human bone morphogenetic protein-2 to enhance tendon healing in a bone tunnel. Am J Sports Med. 1999;27(4):476–88.
62. Weiler A, Peine R, Pashmineh-Azar A, Abel C, Sudkamp NP, Hoffmann RF. Tendon healing in a bone tunnel. Part I: Biomechanical results after biodegradable interference fit fixation in a model of anterior cruciate ligament reconstruction in sheep. Arthroscopy. 2002;18(2):113–23.
63. Amiel D, Kleiner JB, Roux RD, Harwood FL, Akeson WH. The phenomenon of "ligamentization": anterior cruciate ligament reconstruction with autogenous patellar tendon. J Orthop Res. 1986;4(2):162–72.
64. Butler DL, Grood ES, Noyes FR, Olmstead ML, Hohn RB, Arnoczky SP, Siegel MG. Mechanical properties of primate vascularized vs. nonvascularized patellar tendon grafts; changes over time. J Orthop Res. 1989;7(1):68–79. https://doi.org/10.1002/jor.1100070110.
65. Clancy WG, Narechania RG, Rosenberg TD, Gmeiner JG, Wisnefske DD, Lange TA. Anterior and posterior cruciate ligament reconstruction in rhesus monkeys. A histological, microangiographic, and biomechanical analysis. J Bone Joint Surg. 1981;63A(8):1270–84.
66. Weiler A, Peters G, Maurer J, Unterhauser FN, Sudkamp NP. Biomechanical properties and vascularity of an anterior cruciate ligament graft can be predicted by contrast-enhanced magnetic resonance imaging. A two-year study in sheep. Am J Sports Med. 2001;29(6):751–61.
67. Yoshikawa T, Tohyama H, Enomoto H, Matsumoto H, Toyama Y, Yasuda K. Temporal changes in relationships between fibroblast repopulation, VEGF expression, and angiogenesis in the patellar tendon graft after ACL reconstruction. In: Paper presented at the Transactions of the Orthopedic Research. San Francisco, CA; 2003.
68. Ng GY, Oakes BW, Deacon OW, McLean ID, Eyre DR. Long-term study of the biochemistry and biomechanics of anterior cruciate ligament-patellar tendon autografts in goats. J Orthop Res. 1996;14(6):851–6. https://doi.org/10.1002/jor.1100140602.
69. Howell SM, Knox KE, Farley TE, Taylor MA. Revascularization of a human anterior cruciate ligament graft during the first two years of implantation. Am J Sports Med. 1995;23(1):42–9.
70. Weiler A, Unterhauser FN, Bail HJ, Huning M, Haas NP. Alpha-smooth muscle actin is expressed by fibroblastic cells of the ovine anterior cruciate ligament and its free tendon graft during remodeling. J Orthop Res. 2002;20(2):310–7. https://doi.org/10.1016/S0736-0266(01)00109-7.
71. Abe S, Kurosaka M, Iguchi T, Yoshiya S, Hirohata K. Light and electron microscopic study of remodeling and maturation process in autogenous graft for anterior cruciate ligament reconstruction. Arthroscopy. 1993;9(4):394–405.
72. Petersen W, Laprell H. Insertion of autologous tendon grafts to the bone: a histological and immunohistochemical study of hamstring and patellar tendon grafts. Knee Surg Sports Traumatol Arthrosc. 2000;8(1):26–31.
73. Frank CB. Ligament healing: current knowledge and clinical applications. J Am Acad Orthop Surg. 1996;4(2):74–83.
74. Greenlee TK Jr, Pike D. Studies of tendon healing in the rat. Remodeling of the distal stump after severance. Plast Reconstr Surg. 1971;48(3):260–70.

75. Peach R, Williams G, Chapman J. A light and electron optical study of regenerating tendon. Am J Pathol. 1961;38(4):495.
76. Postacchini F, Accinni L, Natali PG, Ippolito E, DeMartino C. Regeneration of rabbit calcaneal tendon: a morphological and immunochemical study. Cell Tissue Res. 1978;195(1):81–97.
77. Bosch U, Kasperczyk WJ. Healing of the patellar tendon autograft after posterior cruciate ligament reconstruction – a process of ligamentization? An experimental study in a sheep model. Am J Sports Med. 1992;20(5):558–66.
78. Ng GY, Oakes BW, Deacon OW, McLean ID, Lampard D. Biomechanics of patellar tendon autograft for reconstruction of the anterior cruciate ligament in the goat: three-year study. J Orthop Res. 1995;13(4):602–8.
79. Yoshiya S, Nagano M, Kurosaka M, Muratsu H, Mizuno K. Graft healing in the bone tunnel in anterior cruciate ligament reconstruction. Clin Orthop Relat Res. 2000;376:278–86.
80. Scheffler SU, Unterhauser FN, Weiler A. Graft remodeling and ligamentization after cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2008;16(9):834–42.
81. Claes S, Verdonk P, Forsyth R, Bellemans J. The "ligamentization" process in anterior cruciate ligament reconstruction: what happens to the human graft? A systematic review of the literature. Am J Sports Med. 2011;39:2476–83.
82. Berg EE, Pollard ME, Kang Q. Interarticular bone tunnel healing. Arthroscopy. 2001;17(2):189–95. https://doi.org/10.1053/jars.2001.20958.
83. Woo SL. Ligament, tendon, and joint capsule insertions to bone. In: Woo SL, Buckwalter JA, editors. Musculoskeletal soft tissues. Chicago: Am Acad Orthop Surg; 1994. p. 136–66.
84. Chen CH. Graft healing in anterior cruciate ligament reconstruction. Sports Med Arthrosc Rehabil Ther Technol. 2009;1(1):21. https://doi.org/10.1186/1758-2555-1-21.
85. Fu FH, Bennett CH, Lattermann C, Ma CB. Current trends in anterior cruciate ligament reconstruction. Part 1: biology and biomechanics of reconstruction. Am J Sports Med. 1999;27(6):821–30.
86. Panni AS, Milano G, Lucania L, Fabbriciani C. Graft healing after anterior cruciate ligament reconstruction in rabbits. Clin Orthop Relat Res. 1997;343:203-212.
87. Ishibashi Y, Toh S, Okamura Y, Sasaki T, Kusumi T. Graft incorporation within the tibial bone tunnel after anterior cruciate ligament reconstruction with bone-patellar tendon-bone autograft. Am J Sports Med. 2001;29(4):473–9. https://doi.org/10.1177/03635465010290041601.
88. Noyes FR, Butler DL, Grood ES, Zernicke RF, Hefzy MS. Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. J Bone Joint Surg Am. 1984;66(3):344–52.
89. Shino K, Nakata K, Horibe S, Inoue M, Nakagawa S. Quantitative evaluation after arthroscopic anterior cruciate ligament reconstruction. Allograft versus autograft. Am J Sports Med. 1993;21(4):609–16.
90. Uchida R, Shiozaki Y, Tanaka Y, Kita K, Amano H, Kanamoto T, Mae T, Tachibana Y, Takao R, Horibe S. Relationship between bone plug position and morphological changes of tunnel aperture in anatomic rectangular tunnel ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2018; https://doi.org/10.1007/s00167-018-5224-8.
91. Bedi A, Kawamura S, Ying L, Rodeo SA. Differences in tendon graft healing between the intra-articular and extra-articular ends of a bone tunnel. HSS J. 2009;5(1):51–7. https://doi.org/10.1007/s11420-008-9096-1.
92. Robert H, Es-Sayeh J, Heymann D, Passuti N, Eloit S, Vaneenoge E. Hamstring insertion site healing after anterior cruciate ligament reconstruction in patients with symptomatic hardware or repeat rupture: a histologic study in 12 patients. Arthroscopy. 2003;19(9):948–54.
93. Kanazawa T, Soejima T, Murakami H, Inoue T, Katouda M, Nagata K. An immunohistological study of the integration at the bone-tendon interface after reconstruction of the anterior cruciate ligament in rabbits. J Bone Joint Surg. 2006;88(5):682–7. https://doi.org/10.1302/0301-620X.88B5.17198.
94. Deehan DJ, Cawston TE. The biology of integration of the anterior cruciate ligament. J Bone Joint Surg. 2005;87(7):889–95. https://doi.org/10.1302/0301-620X.87B7.16038.
95. Weiler A, Scheffler SU, Sudkamp NP. Current aspects of anchoring hamstring tendon transplants in cruciate ligament surgery. Chirurg. 2000;71(9):1034–44.
96. Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: graft options and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 221–57.
97. Schulte K. Radiographic tunnel changes following arthroscopic ACL reconstruction: autograft versus allograft. Arthroscopy. 1995;11:372.
98. Nebelung W, Becker R, Urbach D, Ropke M, Roessner A. Histological findings of tendon-bone healing following anterior cruciate ligament reconstruction with hamstring grafts. Arch Orthop Trauma Surg. 2003;123(4):158–63. https://doi.org/10.1007/s00402-002-0463-y.
99. Rodeo SA, Council on Musculoskeletal Specialty S, American Academy of Orthopaedic S. Whats new in orthopaedic research. J Bone Joint Surg Am. 2003;85-A(10):2054–62.
100. Rodeo SA, Kawamura S, Kim HJ, Dynybil C, Ying L. Tendon healing in a bone tunnel differs at the tunnel entrance versus the tunnel exit: an effect of graft-tunnel motion? Am J

Sports Med. 2006;34(11):1790–800. https://doi.org/10.1177/0363546506290059.
101. Grassman SR, McDonald DB, Thornton GM, Shrive NG, Frank CB. Early healing processes of free tendon grafts within bone tunnels is bone-specific: a morphological study in a rabbit model. Knee. 2002;9(1):21–6.
102. Weiler A, Hoffmann RF, Stahelin AC, Helling HJ, Sudkamp NP. Biodegradable implants in sports medicine: the biological base. Arthroscopy. 2000;16(3):305–21.
103. Weiler A, Helling HJ, Kirch U, Zirbes TK, Rehm KE. Foreign-body reaction and the course of osteolysis after polyglycolide implants for fracture fixation: experimental study in sheep. J Bone Joint Surg. 1996;78(3):369–76.
104. Bostman O, Paivarinta U, Manninen M, Rokkanen P. Polymeric debris from absorbable polyglycolide screws and pins. Intraosseous migration studied in rabbits. Acta Orthop Scand. 1992;63(5):555–9.
105. Lam KH, Schakenraad JM, Esselbrugge H, Feijen J, Nieuwenhuis P. The effect of phagocytosis of poly(L-lactic acid) fragments on cellular morphology and viability. J Biomed Mater Res. 1993;27(12):1569–77. https://doi.org/10.1002/jbm.820271214.
106. Ignatius AA, Claes LE. In vitro biocompatibility of bioresorbable polymers: poly(L, DL-lactide) and poly(L-lactide-co-glycolide). Biomaterials. 1996;17(8):831–9.
107. Daniels A, Taylor M, Andriano K. Heller J toxicity of absorbable polymers proposed for fracture fixation devices. In: Proc Orthop Res Soc; 1992. p. 88.
108. Athanasiou KA, Niederauer GG, Agrawal CM. Sterilization, toxicity, biocompatibility and clinical applications of polylactic acid/polyglycolic acid copolymers. Biomaterials. 1996;17(2):93–102.
109. Singhatat W, Lawhorn KW, Howell SM, Hull ML. How four weeks of implantation affect the strength and stiffness of a tendon graft in a bone tunnel: a study of two fixation devices in an extraarticular model in ovine. Am J Sports Med. 2002;30(4):506–13.
110. Magen HE, Howell SM, Hull ML. Structural properties of six tibial fixation methods for anterior cruciate ligament soft tissue grafts. Am J Sports Med. 1999;27(1):35–43.
111. Tien YC, Chih HW, Cheng YM, Su JY, Weng YP, Lin SY. The influence of the gap size on the interfacial union between the bone and the tendon. Kaohsiung J Med Sci. 1999;15(10):581–8.
112. Greis PE, Burks RT, Bachus K, Luker MG. The influence of tendon length and fit on the strength of a tendon-bone tunnel complex. A biomechanical and histologic study in the dog. Am J Sports Med. 2001;29(4):493–7.
113. Yamazaki S, Yasuda K, Tomita F, Minami A, Tohyama H. The effect of intraosseous graft length on tendon-bone healing in anterior cruciate ligament reconstruction using flexor tendon. Knee Surg Sports Traumatol Arthrosc. 2006;14(11):1086–93. https://doi.org/10.1007/s00167-006-0110-1.
114. Yu JK, Paessler HH. Relationship between tunnel widening and different rehabilitation procedures after anterior cruciate ligament reconstruction with quadrupled hamstring tendons. Chin Med J. 2005;118(4):320–6.
115. Sakai H, Fukui N, Kawakami A, Kurosawa H. Biological fixation of the graft within bone after anterior cruciate ligament reconstruction in rabbits: effects of the duration of postoperative immobilization. J Orthop Sci. 2000;5(1):43–51.
116. Brophy RH, Kovacevic D, Imhauser CW, Stasiak M, Bedi A, Fox AJ, Deng XH, Rodeo SA. Effect of short-duration low-magnitude cyclic loading versus immobilization on tendon-bone healing after ACL reconstruction in a rat model. J Bone Joint Surg Am. 2011;93(4):381–93. https://doi.org/10.2106/JBJS.I.00933.
117. Packer JD, Bedi A, Fox AJ, Gasinu S, Imhauser CW, Stasiak M, Deng XH, Rodeo SA. Effect of immediate and delayed high-strain loading on tendon-to-bone healing after anterior cruciate ligament reconstruction. J Bone Joint Surg Am. 2014;96(9):770–7. https://doi.org/10.2106/JBJS.L.01354.
118. Amis AA, Jakob RP. Anterior cruciate ligament graft positioning, tensioning and twisting. Knee Surg Sports Traumatol Arthrosc. 1998;6(Suppl 1):S2–12.
119. Fleming BC, Abate JA, Peura GD, Beynnon BD. The relationship between graft tensioning and the anterior-posterior laxity in the anterior cruciate ligament reconstructed goat knee. J Orthop Res. 2001;19(5):841–4. https://doi.org/10.1016/S0736-0266(01)00020-1.
120. Markolf KL, Burchfield DM, Shapiro MM, Davis BR, Finerman GA, Slauterbeck JL. Biomechanical consequences of replacement of the anterior cruciate ligament with a patellar ligament allograft. Part I: insertion of the graft and anterior-posterior testing. J Bone Joint Surg Am. 1996;78(11):1720–7.
121. More RC, Markolf KL. Measurement of stability of the knee and ligament force after implantation of a synthetic anterior cruciate ligament. In vitro measurement. J Bone Joint Surg Am. 1988;70(7):1020–31.
122. Yasuda K, Tsujino J, Tanabe Y, Kaneda K. Effects of initial graft tension on clinical outcome after anterior cruciate ligament reconstruction. Autogenous doubled hamstring tendons connected in series with polyester tapes. Am J Sports Med. 1997;25(1):99–106. https://doi.org/10.1177/036354659702500120.
123. Yoshiya S, Andrish JT, Manley MT, Bauer TW. Graft tension in anterior cruciate ligament reconstruction. An in vivo study in dogs. Am J Sports Med. 1987;15(5):464–70.
124. Abramowitch SD, Papageorgiou CD, Withrow JD, Gilbert TW, Woo SL. The effect of initial graft tension on the biomechanical properties of a healing ACL replacement graft: a study in goats. J Orthop Res. 2003;21(4):708–15. https://doi.org/10.1016/S0736-0266(02)00265-6.

125. Yamakado K, Kitaoka K, Yamada H, Hashiba K, Nakamura R, Tomita K. The influence of mechanical stress on graft healing in a bone tunnel. Arthroscopy. 2002;18(1):82–90.
126. Bach BR Jr, Aadalen KJ, Dennis MG, Carreira DS, Bojchuk J, Hayden JK, Bush-Joseph CA. Primary anterior cruciate ligament reconstruction using fresh-frozen, nonirradiated patellar tendon allograft: minimum 2-year follow-up. Am J Sports Med. 2005;33(2):284–92.
127. Barrett G, Stokes D, White M. Anterior cruciate ligament reconstruction in patients older than 40 years: allograft versus autograft patellar tendon. Am J Sports Med. 2005;33(10):1505–12.
128. Hettrich CM, Dunn WR, Reinke EK, Group M, Spindler KP. The rate of subsequent surgery and predictors after anterior cruciate ligament reconstruction: two- and 6-year follow-up results from a multicenter cohort. Am J Sports Med. 2013;41(7):1534–40. https://doi.org/10.1177/0363546513490277.
129. Noyes FR, Barber SD. The effect of a ligament-augmentation device on allograft reconstructions for chronic ruptures of the anterior cruciate ligament. J Bone Joint Surg Am. 1992;74(7):960–73.
130. Noyes FR, Barber-Westin SD, Roberts CS. Use of allografts after failed treatment of rupture of the anterior cruciate ligament. J Bone Joint Surg Am. 1994;76(7):1019–31.
131. Arnoczky SP. Anatomy of the anterior cruciate ligament. Clin Orthop Relat Res. 1983;(172):19–25.
132. Arnoczky SP. Biology of ACL reconstructions: what happens to the graft? Instr Course Lect. 1996;45:229–33.
133. Arnoczky SP, Rubin RM, Marshall JL. Microvasculature of the cruciate ligaments and its response to injury. An experimental study in dogs. J Bone Joint Surg. 1979;61A(8):1221–9.
134. Jackson DW, Simon TM, Kurzweil PR, Rosen MA. Survival of cells after intra-articular transplantation of fresh allografts of the patellar and anterior cruciate ligaments. DNA-probe analysis in a goat model. J Bone Joint Surg Am. 1992;74(1):112–8.
135. Jackson DW, Corsetti J, Simon TM. Biologic incorporation of allograft anterior cruciate ligament replacements. Clin Orthop Relat Res. 1996;324:126–33.
136. Zhang CL, Fan HB, Xu H, Li QH, Guo L. Histological comparison of fate of ligamentous insertion after reconstruction of anterior cruciate ligament: autograft vs allograft. Chin J Traumatol. 2006;9(2):72–6.
137. Jackson DW, Grood ES, Cohn BR, Arnoczky SP, Simon TM, Cummings JF. The effects of in situ freezing on the anterior cruciate ligament. An experimental study in goats. J Bone Joint Surg. 1991;73A(2):201–13.
138. Jackson DW, Grood ES, Arnoczky SP, Butler DL, Simon TM. Freeze dried anterior cruciate ligament allografts. Preliminary studies in a goat model. Am J Sports Med. 1987;15(4):295–303.
139. Jackson DW, Simon TM. Donor cell survival and repopulation after intraarticular transplantation of tendon and ligament allografts. Microsc Res Tech. 2002;58(1):25–33.
140. Rodrigo J, Jackson D, Simon T, Muto K. The immune response to freeze-dried bone-tendon-bone ACL allografts in humans. Am J Knee Surg. 1993;6:47–53.
141. Xiao Y, Parry DA, Li H, Arnold R, Jackson WJ, Bartold PM. Expression of extracellular matrix macromolecules around demineralized freeze-dried bone allografts. J Periodontol. 1996;67(11):1233–44. https://doi.org/10.1902/jop.1996.67.11.1233.
142. Harris NL, Indelicato PA, Bloomberg MS, Meister K, Wheeler DL. Radiographic and histologic analysis of the tibial tunnel after allograft anterior cruciate ligament reconstruction in goats. Am J Sports Med. 2002;30(3):368–73. https://doi.org/10.1177/03635465020300031101.
143. Horstman JK, Ahmadu-Suka F, Norrdin RW. Anterior cruciate ligament fascia lata allograft reconstruction: progressive histologic changes toward maturity. Arthroscopy. 1993;9(5):509–18.
144. Malinin TI, Levitt RL, Bashore C, Temple HT, Mnaymneh W. A study of retrieved allografts used to replace anterior cruciate ligaments. Arthroscopy. 2002;18(2):163–70.
145. Kaeding CC, Pedroza A, Aros BC, Dunn WR, Pifel E, Spindler KP. Independent predictors of ACL reconstruction failure from the MOON prospective longitudinal cohort. In: Paper presented at the AOSSM 2008 annual meeting. Orlando, FL; 2008.
146. Kraeutler MJ, Bravman JT, McCarty EC. Bone-patellar tendon-bone autograft versus allograft in outcomes of anterior cruciate ligament reconstruction: a meta-analysis of 5182 patients. Am J Sports Med. 2013;41(10):2439–48. https://doi.org/10.1177/0363546513484127.
147. Ellis HB, Matheny LM, Briggs KK, Pennock AT, Steadman JR. Outcomes and revision rate after bone-patellar tendon-bone allograft versus autograft anterior cruciate ligament reconstruction in patients aged 18 years or younger with closed physes. Arthroscopy. 2012;28(12):1819–25. https://doi.org/10.1016/j.arthro.2012.06.016.
148. Barrett GR, Luber K, Replogle WH, Manley JL. Allograft anterior cruciate ligament reconstruction in the young, active patient: tegner activity level and failure rate. Arthroscopy. 2010;26(12):1593–601. https://doi.org/10.1016/j.arthro.2010.05.014.
149. Gulotta LV, Rodeo SA. Biology of autograft and allograft healing in anterior cruciate ligament reconstruction. Clin Sports Med. 2007;26(4):509–24. https://doi.org/10.1016/j.csm.2007.06.007.
150. Kondo E, Yasuda K, Katsura T, Hayashi R, Kotani Y, Tohyama H. Biomechanical and histological evaluations of the doubled semitendinosus tendon autograft after anterior cruciate ligament reconstruction in sheep. Am J Sports Med. 2012;40(2):315–24. https://doi.org/10.1177/0363546511426417.

151. Kyung HS, Kim SY, Oh CW, Kim SJ. Tendon-to-bone tunnel healing in a rabbit model: the effect of periosteum augmentation at the tendon-to-bone interface. Knee Surg Sports Traumatol Arthrosc. 2003;11(1):9–15. https://doi.org/10.1007/s00167-002-0317-8.
152. Bolander ME. Inducers of osteogenesis. In: Friedlander GE, Goldberg VM, editors. Bone and cartilage allografts: biology and clinical applications. Park Ridge, IL: American Acadmehy of Orthopaedic Surgeons; 1991. p. 75–83.
153. Kato F. Experimental study of chemical spinal fusion in the rabbit by means of bone morphogenetic protein. Nihon Seikeigeka Gakkai zasshi. 1990;64(5):442–52.
154. Kawaguchi H, Kurokawa T, Hoshino Y, Kawahara H, Ogata E, Matsumoto T. Immunohistochemical demonstration of bone morphogenetic protein-2 and transforming growth factor-beta in the ossification of the posterior longitudinal ligament of the cervical spine. Spine (Phila Pa 1976). 1992;17(3 Suppl):S33–6.
155. Miyamoto S, Takaoka K, Yonenobu K, Ono K. Ossification of the ligamentum flavum induced by bone morphogenetic protein. An experimental study in mice. J Bone Joint Surg. 1992;74(2):279–83.
156. Lind M, Overgaard S, Soballe K, Nguyen T, Ongpipattanakul B, Bunger C. Transforming growth factor-beta 1 enhances bone healing to unloaded tricalcium phosphate coated implants: an experimental study in dogs. J Orthop Res. 1996;14(3):343–50. https://doi.org/10.1002/jor.1100140303.
157. Sumner DR, Turner TM, Purchio AF, Gombotz WR, Urban RM, Galante JO. Enhancement of bone ingrowth by transforming growth factor-beta. J Bone Joint Surg Am. 1995;77(8):1135–47.
158. Woo S-Y. The effect of dose levels of growth factors on the healing of the rabbit medial collateral ligament. Trans Orthop Res Soc. 1996;21:97.
159. Yamazaki S, Yasuda K, Tomita F, Tohyama H, Minami A. The effect of transforming growth factor-beta1 on intraosseous healing of flexor tendon autograft replacement of anterior cruciate ligament in dogs. Arthroscopy. 2005;21(9):1034–41. https://doi.org/10.1016/j.arthro.2005.05.011.
160. Mihelic R, Pecina M, Jelic M, Zoricic S, Kusec V, Simic P, Bobinac D, Lah B, Legovic D, Vukicevic S. Bone morphogenetic protein-7 (osteogenic protein-1) promotes tendon graft integration in anterior cruciate ligament reconstruction in sheep. Am J Sports Med. 2004;32(7):1619–25.
161. Anderson K, Seneviratne AM, Izawa K, Atkinson BL, Potter HG, Rodeo SA. Augmentation of tendon healing in an intraarticular bone tunnel with use of a bone growth factor. Am J Sports Med. 2001;29(6):689–98.
162. Tien YC, Chih TT, Lin JH, Ju CP, Lin SD. Augmentation of tendon-bone healing by the use of calcium-phosphate cement. J Bone Joint Surg. 2004;86(7):1072–6.
163. Dynybil C, Kawamura S, Kim HJ, Ying L, Perka C, Rodeo SA. The effect of osteoprotegerin on tendon-bone healing after reconstruction of the anterior cruciate ligament: a histomorphological and radiographical study in the rabbit. Z Orthop Ihre Grenzgeb. 2006;144(2):179–86. https://doi.org/10.1055/s-2006-921466.
164. Clatworthy MG, Annear P, Bulow J-U, Bartlett RJ. Tunnel widening in anterior cruciate ligament reconstruction: a prospective evaluation of hamstring and patella tendon grafts. Knee Surg Sports Traumatol Arthrosc. 1999;7:138–45.
165. Gomez DE, Alonso DF, Yoshiji H, Thorgeirsson UP. Tissue inhibitors of metalloproteinases: structure, regulation and biological functions. Eur J Cell Biol. 1997;74(2):111–22.
166. Demirag B, Sarisozen B, Ozer O, Kaplan T, Ozturk C. Enhancement of tendon-bone healing of anterior cruciate ligament grafts by blockage of matrix metalloproteinases. J Bone Joint Surg Am. 2005;87(11):2401–10. https://doi.org/10.2106/JBJS.D.01952.
167. Amiel D, Ishizue KK, Harwood FL, Kitabayashi L, Akeson WH. Injury of the anterior cruciate ligament: the role of collagenase in ligament degeneration. J Orthop Res. 1989;7(4):486–93. https://doi.org/10.1002/jor.1100070405.
168. Chubinskaya S, Huch K, Mikecz K, Cs-Szabo G, Hasty KA, Kuettner KE, Cole AA. Chondrocyte matrix metalloproteinase-8: up-regulation of neutrophil collagenase by interleukin-1 beta in human cartilage from knee and ankle joints. Lab Investig. 1996;74(1):232–40.
169. Dahlberg L, Friden T, Roos H, Lark MW, Lohmander LS. A longitudinal study of cartilage matrix metabolism in patients with cruciate ligament rupture--synovial fluid concentrations of aggrecan fragments, stromelysin-1 and tissue inhibitor of metalloproteinase-1. Br J Rheumatol. 1994;33(12):1107–11.
170. Lim JK, Hui J, Li L, Thambyah A, Goh J, Lee EH. Enhancement of tendon graft osteointegration using mesenchymal stem cells in a rabbit model of anterior cruciate ligament reconstruction. Arthroscopy. 2004;20(9):899–910. https://doi.org/10.1016/j.arthro.2004.06.035.
171. Goodman RB, Pugin J, Lee JS, Matthay MA. Cytokine-mediated inflammation in acute lung injury. Cytokine Growth Factor Rev. 2003;14(6):523–35.
172. Leask A, Holmes A, Abraham DJ. Connective tissue growth factor: a new and important player in the pathogenesis of fibrosis. Curr Rheumatol Rep. 2002;4(2):136–42.
173. Singer AJ, Clark RA. Cutaneous wound healing. N Engl J Med. 1999;341(10):738–46. https://doi.org/10.1056/NEJM199909023411006.
174. Kawamura S, Ying L, Kim HJ, Dynybil C, Rodeo SA. Macrophages accumulate in the early phase of tendon-bone healing. J Orthop Res.

2005;23(6):1425–32. https://doi.org/10.1016/j.orthres.2005.01.014.1100230627.
175. Frangogiannis NG, Smith CW, Entman ML. The inflammatory response in myocardial infarction. Cardiovasc Res. 2002;53(1):31–47.
176. Iba O, Matsubara H, Nozawa Y, Fujiyama S, Amano K, Mori Y, Kojima H, Iwasaka T. Angiogenesis by implantation of peripheral blood mononuclear cells and platelets into ischemic limbs. Circulation. 2002;106(15):2019–25.
177. Ignotz RA, Massague J. Transforming growth factor-beta stimulates the expression of fibronectin and collagen and their incorporation into the extracellular matrix. J Biol Chem. 1986;261(9):4337–45.
178. Messner K, Wei Y, Andersson B, Gillquist J, Rasanen T. Rat model of Achilles tendon disorder. A pilot study. Cells Tissues Organs. 1999;165(1):30–9. https://doi.org/10.1159/000016671.
179. Nathan CF. Secretory products of macrophages. J Clin Invest. 1987;79(2):319–26. https://doi.org/10.1172/JCI112815.
180. Marsolais D, Cote CH, Frenette J. Neutrophils and macrophages accumulate sequentially following Achilles tendon injury. J Orthop Res. 2001;19(6):1203–9. https://doi.org/10.1016/S0736-0266(01)00031-6.
181. McLennan IS. Resident macrophages (ED2- and ED3-positive) do not phagocytose degenerating rat skeletal muscle fibres. Cell Tissue Res. 1993;272(1):193–6.
182. Vaage J, Lindblad WJ. Production of collagen type I by mouse peritoneal macrophages. J Leukoc Biol. 1990;48(3):274–80.
183. St Pierre BA, Tidball JG. Differential response of macrophage subpopulations to soleus muscle reloading after rat hindlimb suspension. J Appl Physiol. 1994;77(1):290–7. https://doi.org/10.1152/jappl.1994.77.1.290.
184. Brumsen C, Papapoulos SE, Lentjes EG, Kluin PM, Hamdy NA. A potential role for the mast cell in the pathogenesis of idiopathic osteoporosis in men. Bone. 2002;31(5):556–61.
185. Hiromatsu Y, Toda S. Mast cells and angiogenesis. Microsc Res Tech. 2003;60(1):64–9. https://doi.org/10.1002/jemt.10244.
186. Glaser D, Ramachandran R, Shore E, Lin T, Yeh P, Beredjiklian P, Kaplan F, Goldhamer D, Soslowsky L. The origin of cells within a healing tendon. Trans Orthop Res Soc. 2003;28:340.
187. Harty M, Neff AW, King MW, Mescher AL. Regeneration or scarring: an immunologic perspective. Dev Dyn. 2003;226(2):268–79. https://doi.org/10.1002/dvdy.10239.
188. Hopkinson-Woolley J, Hughes D, Gordon S, Martin P. Macrophage recruitment during limb development and wound healing in the embryonic and foetal mouse. J Cell Sci. 1994;107 (. Pt 5:1159–67.
189. Martin P, D'Souza D, Martin J, Grose R, Cooper L, Maki R, McKercher SR. Wound healing in the PU.1 null mouse--tissue repair is not dependent on inflammatory cells. Curr Biol. 2003;13(13):1122–8.
190. Cohen DB, Kawamura S, Ehteshami JR, Rodeo SA. Indomethacin and celecoxib impair rotator cuff tendon-to-bone healing. Am J Sports Med. 2006;34(3):362–9. https://doi.org/10.1177/0363546505280428.
191. Hoher J, Moller HD, Fu FH. Bone tunnel enlargement after anterior cruciate ligament reconstruction: fact or fiction? Knee Surg Sports Traumatol Arthrosc. 1998;6(4):231–40.
192. L'Insalata JC, Klatt B, Fu FH, Harner CD. Tunnel expansion following anterior cruciate ligament reconstruction: a comparison of hamstring and patellar tendon autografts. Knee Surg Sports Traumatol Arthrosc. 1997;5:234–8.
193. Lajtai G, Schmiedhuber G, Unger F, Aitzetmuller G, Klein M, Noszian I, Orthner E. Bone tunnel remodeling at the site of biodegradable interference screws used for anterior cruciate ligament reconstruction: 5-year follow-up. Arthroscopy. 2001;17(6):597–602.
194. Matsumoto T, Kubo S, Sasaki K, Kawakami Y, Oka S, Sasaki H, Takayama K, Tei K, Matsushita T, Mifune Y, Kurosaka M, Kuroda R. Acceleration of tendon-bone healing of anterior cruciate ligament graft using autologous ruptured tissue. Am J Sports Med. 2012;40(6):1296–302. https://doi.org/10.1177/0363546512439026.
195. Sasaki K, Kuroda R, Ishida K, Kubo S, Matsumoto T, Mifune Y, Kinoshita K, Tei K, Akisue T, Tabata Y, Kurosaka M. Enhancement of tendon-bone osteointegration of anterior cruciate ligament graft using granulocyte colony-stimulating factor. Am J Sports Med. 2008;36(8):1519–27. https://doi.org/10.1177/0363546508316282.
196. Webster KE, Chiu JJ, Feller JA. Impact of measurement error in the analysis of bone tunnel enlargement after anterior cruciate ligament reconstruction. Am J Sports Med. 2005;33(11):1680–7. https://doi.org/10.1177/0363546505275489.
197. Ferretti M, Ekdahl M, Shen W, Fu FH. Osseous landmarks of the femoral attachment of the anterior cruciate ligament: an anatomic study. Arthroscopy. 2007;23(11):1218–25.
198. White LM, Kramer J, Recht MP. MR imaging evaluation of the postoperative knee: ligaments, menisci, and articular cartilage. Skelet Radiol. 2005;34(8):431–52. https://doi.org/10.1007/s00256-005-0914-y.
199. Ntoulia A, Papadopoulou F, Ristanis S, Argyropoulou M, Georgoulis AD. Revascularization process of the bone--patellar tendon--bone autograft evaluated by contrast-enhanced magnetic resonance imaging 6 and 12 months after anterior cruciate ligament reconstruction. Am J Sports Med. 2011;39(7):1478–86. https://doi.org/10.1177/0363546511398039.
200. Gnannt R, Chhabra A, Theodoropoulos JS, Hodler J, Andreisek G. MR imaging of the postoperative

knee. J Magn Reson Imaging. 2011;34(5):1007–21. https://doi.org/10.1002/jmri.22672.
201. Kulczycka P, Larbi A, Malghem J, Thienpont E, Vande Berg B, Lecouvet F. Imaging ACL reconstructions and their complications. Diagn Interv Imaging. 2015;96(1):11–9. https://doi.org/10.1016/j.diii.2014.04.007.
202. Naraghi A, White L. MRI evaluation of the postoperative knee: special considerations and pitfalls. Clin Sports Med. 2006;25(4):703–25. https://doi.org/10.1016/j.csm.2006.06.007.
203. Rabuck SJ, Baraga MG, Fu FH. Anterior cruciate ligament healing and advances in imaging. Clin Sports Med. 2013;32(1):13–20. https://doi.org/10.1016/j.csm.2012.08.003.
204. Li X, Kuo D, Theologis A, Carballido-Gamio J, Stehling C, Link TM, Ma CB, Majumdar S. Cartilage in anterior cruciate ligament-reconstructed knees: MR imaging T1{rho} and T2--initial experience with 1-year follow-up. Radiology. 2011;258(2):505–14. https://doi.org/10.1148/radiol.10101006.
205. White LM, Sussman MS, Hurtig M, Probyn L, Tomlinson G, Kandel R. Cartilage T2 assessment: differentiation of normal hyaline cartilage and reparative tissue after arthroscopic cartilage repair in equine subjects. Radiology. 2006;241(2):407–14. https://doi.org/10.1148/radiol.2412051750.
206. Fleming BC, Vajapeyam S, Connolly SA, Magarian EM, Murray MM. The use of magnetic resonance imaging to predict ACL graft structural properties. J Biomech. 2011;44(16):2843–6. https://doi.org/10.1016/j.jbiomech.2011.09.004.
207. Ma CB, Francis K, Towers J, Irrgang J, Fu FH, Harner CH. Hamstring anterior cruciate ligament reconstruction: a comparison of bioabsorbable interference screw and endobutton-post fixation. Arthroscopy. 2004;20(2):122–8. https://doi.org/10.1016/j.arthro.2003.11.007.
208. Konan S, Haddad FS. Femoral fracture following knee ligament reconstruction surgery due to an unpredictable complication of bioabsorbable screw fixation: a case report and review of literature. J Orthop Traumatol. 2010;11(1):51–5. https://doi.org/10.1007/s10195-009-0079-x.
209. Achtnich A, Forkel P, Metzlaff S, Zantop T, Petersen W. Degradation of poly-D-L-lactide (PDLLA) interference screws (Megafix (R)). Arch Orthop Trauma Surg. 2014;134(8):1147–53. https://doi.org/10.1007/s00402-014-2013-9.
210. White LM, Buckwalter KA. Technical considerations: CT and MR imaging in the postoperative orthopedic patient. Semin Musculoskelet Radiol. 2002;6(1):5–17. https://doi.org/10.1055/s-2002-23160.
211. Grassi A, Bailey JR, Signorelli C, Carbone G, Tchonang Wakam A, Lucidi GA, Zaffagnini S. Magnetic resonance imaging after anterior cruciate ligament reconstruction: a practical guide. World J Orthop. 2016;7(10):638–49. https://doi.org/10.5312/wjo.v7.i10.638.
212. Rahmer J, Bornert P, Dries SP. Assessment of anterior cruciate ligament reconstruction using 3D ultrashort echo-time MR imaging. J Magn Reson Imaging. 2009;29(2):443–8. https://doi.org/10.1002/jmri.21653.
213. Biercevicz AM, Miranda DL, Machan JT, Murray MM, Fleming BC. In situ, noninvasive, T2∗-weighted MRI-derived parameters predict ex vivo structural properties of an anterior cruciate ligament reconstruction or bioenhanced primary repair in a porcine model. Am J Sports Med. 2013;41(3):560–6. https://doi.org/10.1177/0363546512472978.
214. Biercevicz AM, Murray MM, Walsh EG, Miranda DL, Machan JT, Fleming BC. T2 ∗ MR relaxometry and ligament volume are associated with the structural properties of the healing ACL. J Orthop Res. 2014;32(4):492–9. https://doi.org/10.1002/jor.22563.
215. Chu CR, Williams AA, West RV, Qian Y, Fu FH, Do BH, Bruno S. Quantitative magnetic resonance imaging UTE-T2∗ mapping of cartilage and meniscus healing after anatomic anterior cruciate ligament reconstruction. Am J Sports Med. 2014;42(8):1847–56. https://doi.org/10.1177/0363546514532227.
216. Koff MF, Shah P, Pownder S, Romero B, Williams R, Gilbert S, Maher S, Fortier LA, Rodeo SA, Potter HG. Correlation of meniscal T2∗ with multiphoton microscopy, and change of articular cartilage T2 in an ovine model of meniscal repair. Osteoarthr Cartil. 2013;21(8):1083–91. https://doi.org/10.1016/j.joca.2013.04.020.
217. Qian Y, Williams AA, Chu CR, Boada FE. High-resolution ultrashort echo time (UTE) imaging on human knee with AWSOS sequence at 3.0 T. J Magn Reson Imaging. 2012;35(1):204–10. https://doi.org/10.1002/jmri.22639.
218. Qian Y, Williams AA, Chu CR, Boada FE. Repeatability of ultrashort echo time-based two-component T2∗ measurements on cartilages in human knee at 3 T. Magn Reson Med. 2013;69(6):1564–72. https://doi.org/10.1002/mrm.24392.
219. Williams A, Qian Y, Golla S, Chu CR. UTE-T2 ∗ mapping detects sub-clinical meniscus injury after anterior cruciate ligament tear. Osteoarthr Cartil. 2012;20(6):486–94. https://doi.org/10.1016/j.joca.2012.01.009.
220. Roberts TP, Schwartz ES. Principles and implementation of diffusion-weighted and diffusion tensor imaging. Pediatr Radiol. 2007;37(8):739–48. https://doi.org/10.1007/s00247-007-0516-z.
221. Pierpaoli C, Jezzard P, Basser PJ, Barnett A, Di Chiro G. Diffusion tensor MR imaging of the human brain. Radiology. 1996;201(3):637–48. https://doi.org/10.1148/radiology.201.3.8939209.
222. Brander A, Kataja A, Saastamoinen A, Ryymin P, Huhtala H, Ohman J, Soimakallio S, Dastidar P. Diffusion tensor imaging of the brain in a healthy adult population: normative values and measurement reproducibility at 3 T and 1.5 T. Acta Radiol. 2010;51(7):800–7. https://doi.org/10.3109/02841851.2010.495351.
223. Chen L, Zhao H, Li J, Quan X, Qing W, Liu W, Liu J. Diffusion tensor imaging map of anterior

cruciate ligament contrasted with MRI in healthy adults. Zhong Nan Da Xue Xue Bao Yi Xue Ban. 2013;38(6):610–6. https://doi.org/10.3969/j.issn.1672-7347.2013.06.010.
224. Yang X, Li M, Chen D, Shi D, Zhou Z, Zhu B, Jiang Q. Diffusion tensor imaging for anatomical and quantitative evaluation of the anterior cruciate ligament and ACL grafts: a preliminary study. J Comput Assist Tomogr. 2014;38(4):489–94. https://doi.org/10.1097/RCT.0000000000000078.
225. de Sa D, Fu FH. Fresh Osteochondral allograft transplantation is an effective salvage strategy for revision of failed cartilage repair: commentary on an article by Tim Wang, MD, et al.: "clinical and MRI outcomes of fresh Osteochondral allograft transplantation after failed cartilage repair surgery in the knee". J Bone Joint Surg Am. 2018;100(22):e145. https://doi.org/10.2106/JBJS.18.00805.
226. Webster KE, Feller JA, Leigh WB, Richmond AK. Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. Am J Sports Med. 2014;42(3):641–7. https://doi.org/10.1177/0363546513517540.
227. Engelman GH, Carry PM, Hitt KG, Polousky JD, Vidal AF. Comparison of allograft versus autograft anterior cruciate ligament reconstruction graft survival in an active adolescent cohort. Am J Sports Med. 2014;42(10):2311–8. https://doi.org/10.1177/0363546514541935.
228. Barber FA, Cowden CH 3rd, Sanders EJ. Revision rates after anterior cruciate ligament reconstruction using bone-patellar tendon-bone allograft or autograft in a population 25 years old and younger. Arthroscopy. 2014;30(4):483–91. https://doi.org/10.1016/j.arthro.2013.12.022.
229. Sherman MF, Lieber L, Bonamo JR, Podesta L, Reiter I. The long-term followup of primary anterior cruciate ligament repair. Defining a rationale for augmentation. Am J Sports Med. 1991;19(3):243–55. https://doi.org/10.1177/036354659101900307.
230. van der List JP, DiFelice GS. Preservation of the anterior cruciate ligament: a treatment algorithm based on tear location and tissue quality. Am J Orthop (Belle Mead NJ). 2016;45(7):E393–405.
231. van der List JP, Mintz DN, DiFelice GS. The location of anterior cruciate ligament tears: a prevalence study using magnetic resonance imaging. Orthop J Sports Med. 2017;5(6):2325967117709966. https://doi.org/10.1177/2325967117709966.
232. Vavken P, Fleming BC, Mastrangelo AN, Machan JT, Murray MM. Biomechanical outcomes after bioenhanced anterior cruciate ligament repair and anterior cruciate ligament reconstruction are equal in a porcine model. Arthroscopy. 2012;28(5):672–80. https://doi.org/10.1016/j.arthro.2011.10.008.
233. Adachi N, Ochi M, Uchio Y, Iwasa J, Ryoke K, Kuriwaka M. Mechanoreceptors in the anterior cruciate ligament contribute to the joint position sense. Acta Orthop Scand. 2002;73(3):330–4. https://doi.org/10.1080/000164702320155356.
234. DiFelice GS, Villegas C, Taylor S. Anterior cruciate ligament preservation: early results of a novel arthroscopic technique for suture anchor primary anterior cruciate ligament repair. Arthroscopy. 2015;31(11):2162–71. https://doi.org/10.1016/j.arthro.2015.08.010.
235. Murray MM. Current status and potential of primary ACL repair. Clin Sports Med. 2009;28(1):51–61. https://doi.org/10.1016/j.csm.2008.08.005.
236. van der List JP, DiFelice GS. Range of motion and complications following primary repair versus reconstruction of the anterior cruciate ligament. Knee. 2017;24(4):798–807. https://doi.org/10.1016/j.knee.2017.04.007.
237. Nguyen DT, Geel J, Schulze M, Raschke MJ, Woo SL, van Dijk CN, Blankevoort L. Healing of the goat anterior cruciate ligament after a new suture repair technique and bioscaffold treatment. Tissue Eng Part A. 2013;19(19–20):2292–9. https://doi.org/10.1089/ten.TEA.2012.0535.
238. Nguyen DT, Ramwadhdoebe TH, van der Hart CP, Blankevoort L, Tak PP, van Dijk CN. Intrinsic healing response of the human anterior cruciate ligament: an histological study of reattached ACL remnants. J Orthop Res. 2014;32(2):296–301.
239. Kohl S, Evangelopoulos DS, Ahmad SS, Kohlhof H, Herrmann G, Bonel H, Eggli S. A novel technique, dynamic intraligamentary stabilization creates optimal conditions for primary ACL healing: a preliminary biomechanical study. Knee. 2014;21(2):477–80.
240. Buchler L, Regli D, Evangelopoulos DS, Bieri K, Ahmad SS, Krismer A, Muller T, Kohl S. Functional recovery following primary ACL repair with dynamic intraligamentary stabilization. Knee. 2016;23(3):549–53. https://doi.org/10.1016/j.knee.2016.01.012.
241. Evangelopoulos DS, Kohl S, Schwienbacher S, Gantenbein B, Exadaktylos A, Ahmad SS. Collagen application reduces complication rates of midsubstance ACL tears treated with dynamic intraligamentary stabilization. Knee Surg Sports Traumatol Arthrosc. 2017;25(8):2414–9.
242. Kosters C, Herbort M, Schliemann B, Raschke MJ, Lenschow S. Dynamic intraligamentary stabilization of the anterior cruciate ligament. Operative technique and short-term clinical results. Unfallchirurg. 2015;118(4):364–71. https://doi.org/10.1007/s00113-015-2745-1.
243. Kohl S, Evangelopoulos DS, Kohlhof H, Hartel M, Bonel H, Henle P, von Rechenberg B, Eggli S. Anterior crucial ligament rupture: self-healing through dynamic intraligamentary stabilization technique. Knee Surg Sports Traumatol Arthrosc. 2013;21(3):599–605. https://doi.org/10.1007/s00167-012-1958-x.
244. Malahias M-A, Chytas D, Nakamura K, Raoulis V, Yokota M, Nikolaou VS. A narrative review of four different new techniques in primary anterior cruciate ligament repair:"Back to the future" or another trend? Sports Med-Open. 2018;4(1):37.

Check for updates

8 Preoperative Rehabilitation: Basic Principles

Timothy P. Heckmann, Frank R. Noyes, and Sue Barber-Westin

8.1 Introduction

Patients with acute ACL injuries typically present with a painful, swollen knee with limited range of motion (ROM) and severe muscle guarding or inhibition. Several studies have documented increased incidences of complications and poorer outcomes after ACL reconstruction when surgery is performed within a few weeks of the injury or before resolution of swelling, pain, muscle weakness and inhibition, abnormal gait mechanics, and ROM limitations [1–5]. A systematic review encompassing 18 high-quality studies found that smoking, high body mass index, poor quadriceps strength (>20% deficit), and ROM deficits before surgery had a negative effect on postoperative outcomes [6]. An exception to early reconstruction is a concomitant displaced bucket-handle meniscus tear in which surgery is performed within 7–10 days to reduce the meniscus to a normal location and repair the tear [7]. Knees with concomitant major tears to other ligaments are treated according to the complexity of the injury; these complex cases are beyond the scope of this chapter and have been discussed in detail elsewhere [8–10]. Otherwise, patients with acute ACL ruptures require resolution of the injury effects and then restoration of normal gait and muscle function before ACL reconstruction is considered (Table 8.1). We believe that a comprehensive rehabilitation program before ACL reconstruction is crucial for all patients with ACL ruptures (Tables 8.2 and 8.3), and multiple studies have documented the advantages of formal preoperative therapy in terms of restoration of ROM, muscle strength, and neuromuscular function [11–16].

Patients with chronic ACL injuries may require weeks or even months of rehabilitation to restore muscle strength and neuromuscular function to appropriate levels before surgery. Activity modification is required to avoid further reinjuries of either partial or full giving-way. Prior

Table 8.1 Preoperative issues to resolve before ACL reconstruction

1. Limitation of full knee motion
2. Muscle atrophy
3. Gait abnormalities
4. Pain
5. Knee joint effusion
6. Any psychological factors such as poor motivation or fear
7. Any potential compliance problems with postoperative rehabilitation

T. P. Heckmann
Jewish Hospital Orthopaedic Sports Medicine and Rehabilitation, Cincinnati, OH, USA

Noyes Knee Institute, Cincinnati, OH, USA

F. R. Noyes · S. Barber-Westin (✉)
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_8

Table 8.2 Noyes Knee Institute 6-week preoperative rehabilitation protocol for acute ACL tears

	Phases/Weeks		
	Phase 1 Week 1	Phase 2 Weeks 2–3	Phase 3 Weeks 4–6
Range of motion goals:			
0–120°	X		
0–135°		X	X
Weight bearing[a] (with soft elastic knee sleeve):			
3/4 body weight	X		
Full		X	X
Patella mobilization	X	if required	
Modalities:			
Electrical muscle stimulation	X	X	
Biofeedback	X	X	
Pain/edema management (cryotherapy)	X	X	X
Stretching:			
Hamstring, gastrocsoleus, iliotibial band, quadriceps	X	X	X
Strengthening:			
Quadriceps isometrics, straight leg raises (all four planes)	X	X	X
Active knee extension (90–30°)	X		
Active knee extension (90–0°)		X	X
Gait retraining, toe raises, wall sits, mini-squats	X	X	X
Hamstring curls machine (0–90°)	X	X	X
Knee extension machine (90–30°)		X	X
Hip abduction–adduction, multi-hip		X	X
Leg press (80–10°)		X	X
Upper body weight training		X	X
Core training		X	X
Balance/proprioceptive training:			
Passive–active joint repositioning	X		
Weight shifting, cup walking	X	X	
BBS, BAPS, perturbation training, balance board, mini-trampoline		X	X
Conditioning:			
Bike (stationary)		X	X
Swimming (kicking)			X
Walking			X
Stair climbing machine			X
Ski machine		X	X
Elliptical machine		X	X

BAPS biomechanical ankle platform system, *BBS* Biodex balance system
[a]Some patients may require crutch support for 3–4 weeks for walking and stair climbing, based on pain, swelling, muscle weakness, poor gait

meniscectomy or existing articular cartilage damage complicates the course of treatment in these patients [6]. Individuals who present after prior failed ACL reconstruction will most likely have inferior outcomes compared with patients who present with first-time acute ACL injury [17]. Before surgery, expectations of the outcome of surgery should be addressed, along with any psychological concerns such as potential poor compliance with postoperative rehabilitation, reinjury anxiety, poor perceived self-efficacy, or internal locus of control. The identification of these problems before surgery allows for appropriate counseling and implementation of other treatment options throughout the postoperative period [18, 19].

Table 8.3 Goals for each phase of preoperative rehabilitation

Phase	Goals
1 Week 1	– Range of knee motion, 0–120° – Soft knee sleeve for support and compression – Adequate quadriceps contraction – Control joint effusion, inflammation, pain – 75% weight bearing with crutches
2 Weeks 2–3	– Range of knee motion full – Soft knee sleeve for support – Good quadriceps contraction – Control joint effusion, inflammation, pain – Full weight bearing (some patients may require crutch support for 3–4 weeks for walking and stair climbing, based on pain, swelling, muscle weakness, poor gait)
3 Weeks 4–6	– Range of knee motion full – Soft knee sleeve for support – Good quadriceps contraction, muscle endurance – Control joint effusion, inflammation – Normal gait – No pain – Mentally prepared for surgery

8.2 Issues to Treat and Resolve Before ACL Reconstruction

8.2.1 Hemarthrosis and Knee Joint Effusion

The inflammatory response to the initial ACL injury varies among patients. While some individuals have little effusion and swelling, others have an exaggerated inflammatory response characterized by pain, soft tissue edema, and redness and increased warmth to tissues surrounding the knee. Hemarthrosis is common following acute ACL ruptures [20] and should be treated immediately with joint aspiration. Wang et al. [21] studied the effect of aspiration of hemarthrosis performed in the emergency room (ER) after acute ACL injury on pain, ROM, and accuracy of diagnosis of the ACL tear during the first orthopedic surgeon office visit performed 7–14 days later. Eighteen patients who underwent joint aspiration in the ER had significantly greater ROM compared with 42 patients who did not undergo aspiration (100 ± 30° and 92.6 ± 31°, respectively; $P = 0.001$), had a significantly higher percentage with a positive Lachman test (76.5% and 47.6%, respectively; $P < 0.05$), and had a significantly higher percentage with a positive pivot shift test (76.5% and 31%, respectively, $P < 0.001$). All patients in this study eventually underwent ACL reconstruction.

Studies have demonstrated that experimentally induced knee joint effusions inhibited quadriceps muscle function and produced alterations in normal function during walking, jogging, and landing from a jump [22, 23]. For instance, Palmieri-Smith et al. [22] reported significant decreases ($P < 0.05$) in vastus medialis and vastus lateralis activity after 30 mL and 60 mL saline injections in healthy subjects. In addition, a significant decrease was found in the mean peak knee flexion angle on a single-leg drop-land task in subjects who received 60 mL of saline compared with those who received either 3 mL of 1% Xylocaine or controls (36.30° compared with 46.05° and 47.39°, respectively; $P < 0.05$). Mean peak ground reaction forces were significantly larger after 60 mL injections compared with Xylocaine and control groups (55.26 Nm/kg compared with 44.88 and 43.27 Nm/kg, respectively; $P < 0.05$), while net peak knee extension moments were significantly smaller after 60 mL injections (3.37 BW compared with 1.87 and 1.61 BW, respectively; $P < 0.05$).

Therefore, hemarthroses and joint effusions must be treated to lessen their potentially deleterious impacts on quadriceps function and knee joint mechanics. Joint aspiration, cryotherapy, elevation of the limb above the heart, and compression are effective therapeutic measures. Prudent, short-term use of non-steroidal anti-inflammatory medications may also be required. Knees with an exaggerated inflammatory reaction to the ACL injury are treated conservatively for as long as required to resolve these problems before surgery is considered, and are also carefully monitored after ACL reconstruction for a similar inflammatory reaction postoperatively. These individuals may require a trial of oral steroids if NSAID fails to resolve the inflammation.

8.2.2 Limitations in Knee Motion

Performing ACL reconstruction within a few weeks of the injury or before the resolution of swelling, pain, quadriceps muscle atrophy, abnormal gait mechanics, and ROM limitations has been noted to correlate with postoperative knee motion problems [2–5, 24–28]. Shelbourne et al. [2] noted an increased rate of arthrofibrosis in patients who underwent ACL reconstruction within 7 days of the injury compared with those in whom surgery was delayed for at least 21 days. Wasilewski et al. [5] documented arthrofibrosis in 22% of acutely reconstructed knees compared with 12.5% of knees reconstructed with chronic ACL deficiency. Mauro et al. [3] followed 229 patients who underwent ACL reconstruction and reported that 25% had not regained full knee extension at 4 weeks postoperative. Compared with the group of patients who had regained full extension, the group that had a limitation were noted to have had a shorter mean time from injury to surgery (60 days and 93 days, respectively; $P < 0.05$), a greater amount of loss of extension before surgery (4° and 1°, respectively; $P < 0.05$), and a greater percentage that underwent autograft reconstruction than allograft reconstruction (28.5% and 14%, respectively; $P < 0.05$). Investigators have advocated the need to delay surgery until knee motion is regained, swelling is resolved, and a good quadriceps contraction is demonstrated [25, 29].

Knee motion exercises are performed immediately upon diagnosis of acute ACL tears in an effort to decrease pain and prevent scar tissue formation. The majority of patients present with some loss of motion, and our goal is to obtain at least 0–135° within 2–3 weeks of the injury. The detrimental effects of knee joint immobilization are well recognized and include permanent limitation of knee motion, prolonged muscle atrophy, patella infera, abnormal joint arthrokinematics, increased contact pressures in the patellofemoral and/or tibiofemoral joints, and patellofemoral osteoarthritis [30–33]. Range of motion exercises are accompanied by patellar mobilization in the superior–inferior and medial–lateral directions.

For patients who have difficulty achieving these knee motion goals, overpressure exercises are initiated to gradually stretch capsular tissues (Table 8.4). One effective exercise for extension involves hanging weights (Fig. 8.1), in which the foot and ankle are propped on a towel or other device to elevate the hamstrings and gastrocnemius, which allows the knee to drop into full extension (see also Chap. 11). This position is maintained for 10–15 min and repeated at least eight times per day. Initially a 10-pound weight is used, which may be progressed up to 25 pounds to the distal thigh and knee to provide overpressure to stretch the posterior contracted tissues. Flexion limitations may be resolved using overpressure exercises such as a rolling stool maneuver or wall sliding (Fig. 8.2, see also Chap. 11). Commercial knee flexion devices may also be used as available to further promote overpressure.

Table 8.4 Noyes Knee Institute protocols for limitation of knee motion

Extension limitations: Hanging weight exercise: prefer supine position (may elect prone position), prop the foot and ankle on a towel or other device to elevate the hamstrings and gastrocnemius to allow the knee to drop into full extension – Add 10 lb weight to the distal thigh to provide overpressure to stretch the posterior capsule – Maintain for 10–15 min and repeat 4–8×/day – Add more weight (up to 25 lb) if full extension not achieved within a week Commercially available extension board
Flexion limitations: Rolling stool exercise: sit on a small stool close to the ground, flex the knee to its maximum position possible, hold that position for 1–2 min. Then, gently roll the stool forward without moving the foot to achieve a few more degrees of flexion Wall slide exercise: lie on the back and place the foot of the injured knee on a wall with the knee flexed. Use the foot of the opposite leg to gently slide the opposite foot and further flex the injured knee in a gradual manner Commercially available knee flexion devices

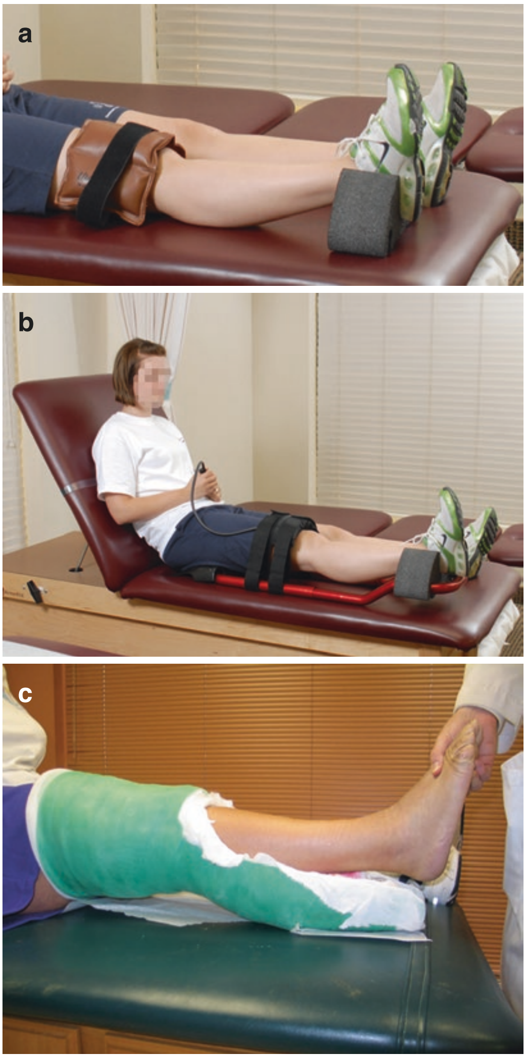


Fig. 8.1 Options to regain full knee extension include (**a**) hanging weights, (**b**) extension board, and for difficult cases, (**c**) a drop-out cast. (Reprinted from Noyes and Barber-Westin [64])

Crutch support is used as required based on pain, swelling, muscle weakness, and poor gait mechanics.

8.2.3 Loss of Muscle Strength

Neuromuscular electrical muscle stimulation (EMS) and biofeedback are used to aid in the initial recovery of quadriceps activation after acute ACL tears. Several studies demonstrated that EMS combined with exercise was more effective than exercise alone in recovery of quadriceps strength and normal gait mechanics following ACL reconstruction, and we believe these concepts also apply to the treatment of acute ACL injuries [34–39]. A combination of closed kinetic chain (CKC) and open kinetic chain (OKC) exercises are begun immediately, including wall sits, mini-squats (Fig. 8.3), quadriceps isometrics at 0°, straight leg raises in all four planes, active knee extension from 90–30°, side-lying clams (Fig. 8.4), and hamstring curls from 0–90° (Table 8.5). The OKC exercises selected have been shown not to adversely affect anterior tibial translation [40–45].

The therapist should understand the impact that exercises and machines may have on the patellofemoral joint (see Chap. 11) and avoid high-force exercises that involve deep knee flexion angles (i.e., deep squatting, kneeling past 50°, and extensive stair climbing). We recommend using the knee extension machine in the range of 90–30°, the leg press machine in the range of 80–10°, mini-squats to 45° of knee flexion, wall sits to 50° of flexion, lateral step-ups, and forward step-ups.

It is also important for the therapist to realize that technique during certain activities affects muscle recruitment and ACL loading. For instance, a forward trunk position of 30–40° during a mini-squat will recruit greater hamstrings activity and lessen ACL loading, while an erect trunk position results in greater quadriceps activation and increased ACL loading [46, 47]. Forward and lateral lunges are effective due to the relatively high hamstrings activation and are initiated during Phase 2, based on patient's pain tolerance. The strengthening program includes hip, upper body, and core training which are initiated during Phase 2 and continue through the end of the preoperative program (see Table 8.2).

Fig. 8.2 Options to regain full knee flexion include (**a**, **b**) wall slides, (**c**) flexion seat, and (**d**) knee flexion overpressure device. (Reprinted from Heckmann et al. [65])

8.2.4 Impairments in Neuromuscular Function

ACL injuries may cause alterations in knee joint proprioception (sense of awareness of the joint position), abnormal muscle activation patterns, and reduced dynamic joint stability [48–54]. Proprioception is altered from damage incurred to the joint mechanoreceptors and muscle afferents and may be further impaired with a concurrent meniscus tear [55, 56]. Proprioception is considered by many to be a crucial element of neuromuscular function, and its recovery is essential for a successful outcome [30, 57]. Dynamic postural control or stability is another important neuromuscular factor that must be restored. Impairment in postural stability is believed to be related, in part, to deficiencies in proprioception [58, 59]. Balance requires constant adjustment to the body's muscular activity

Fig. 8.3 Closed kinetic chain exercises include (**a**) mini-squats, (**b**) wall sits, and (**c**) the leg press machine. (Reprinted from Heckmann et al. [65])

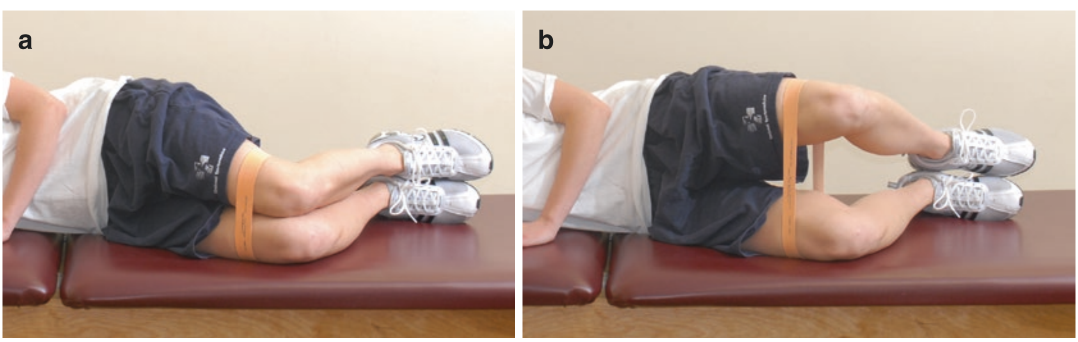


Fig. 8.4 The hip abductors exercised using a side-lying "clam" exercise which may be performed with (**a**, **b**) or without a resistance band. (Reprinted from Heckmann et al. [65])

Table 8.5 Noyes Knee Institute 6-week preoperative rehabilitation protocol for ACL tears: muscle strengthening exercises

Time post, frequency, duration	Quadriceps isometrics (active)	Straight leg raises	Active knee extension	Toe raises, heel raises	Wall sits (to fatigue)	Mini-squats	Lunges	Side-lying clams	Knee extension machine (90–30°)	Hamstring curl machine (0–90°)	Multi-hip	Leg press (80–10°)
Phase 1 Week 1 3–4 times per day	3 sets × 10 reps 0°	All four planes 3 sets × 10 reps	3 sets × 10 reps, 90–30°	3 sets × 10 reps	75% weight bearing: 5 reps	0–45°, 75% weight bearing: 3 sets × 20 reps				3 sets × 10 reps		
Phase 2 Weeks 2–3 2–3 times per day	Multi-angle: 90°, 60°, 30° 2 sets × 10 reps each angle	All four planes 3 sets × 10 reps	3 sets × 10 reps, 90–0°	3 sets × 10 reps	5 reps	3 sets × 10 reps on stability platform	Straight	With resistance band	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps
Phase 3 Weeks 4–6 1–2 × times per day	Multi-angle: 30°, 60°, 90° 3 sets × 10 reps each angle	All four planes with ankle weight (≤10% of body weight): 3 sets × 10 reps	3 sets × 10 reps, 90–0°	3 sets × 10 reps	5 reps Wall slides with physioball	3 sets × 20 reps on unstable surface	Lateral with resistance cord	With resistance band	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps

Reps repetitions

and positioning and is influenced by the integration of sensory-motor information into the central nervous system and the resultant motor response. The alterations in proprioception, muscle strength and activation patterns, and dynamic joint stability may affect the opposite lower extremity, and several studies have reported high injury rates to the contralateral knee upon RTS [60–63]. Therefore, the rehabilitation program must include both extremities to lessen these deleterious effects.

Proprioception and postural stability exercises are begun immediately and gradually progressed in difficulty (Table 8.6). Passive–active joint repositioning and weight shifting are initiated, as well as walking over cups in forward, backward, and sideways positions based on patient's tolerance (Fig. 8.5). Walking on half foam rolls and walking with exaggerated hip flexion with or without a resistance band around the thighs (Fig. 8.6) are also part of the gait retraining and balance program. These exercises help the patient

Table 8.6 Noyes Knee Institute 6-week preoperative rehabilitation protocol for ACL tears: balance and proprioception exercises performed in clinic

Time	Joint repositioning	Weight shifting	Cup walking	Single-leg stance	Step-downs	Resistance band walking	Plyoback ball toss	Perturbation training
Phase 1 Week 1	Therapist passively moves knee into various angular positions, patient with eyes closed actively reproduces same flexion angles. 10 reps	Side–side and forward–backward, 50% weight bearing, 5 sets × 10 reps	Cup height 2–3″, 5 mins					
Phase 2 Weeks 2–3		Side–side and forward–backward, 75% weight bearing, 5 sets × 10 reps. May do on Biodex balance system for visual cues	Cup height 3–4″, 5 min	Level surface 30 s × 5 reps	2–4″ block onto stable surface 1–3 sets × 10 reps	Forward and sideways 5 min		
Phase 3 Weeks 4–6				Unstable surface 30 s × 5 reps	2–4″ block onto unstable surface or 4–6″ block onto stable surface 1–3 sets × 10 reps	All directions 5 min	Double-leg to single-leg. Stable to unstable surface. 3 sets × 10 reps chest pass or overhead soccer throw	Side–side rocker board or use Biodex stabilometer 60 s × 3 reps

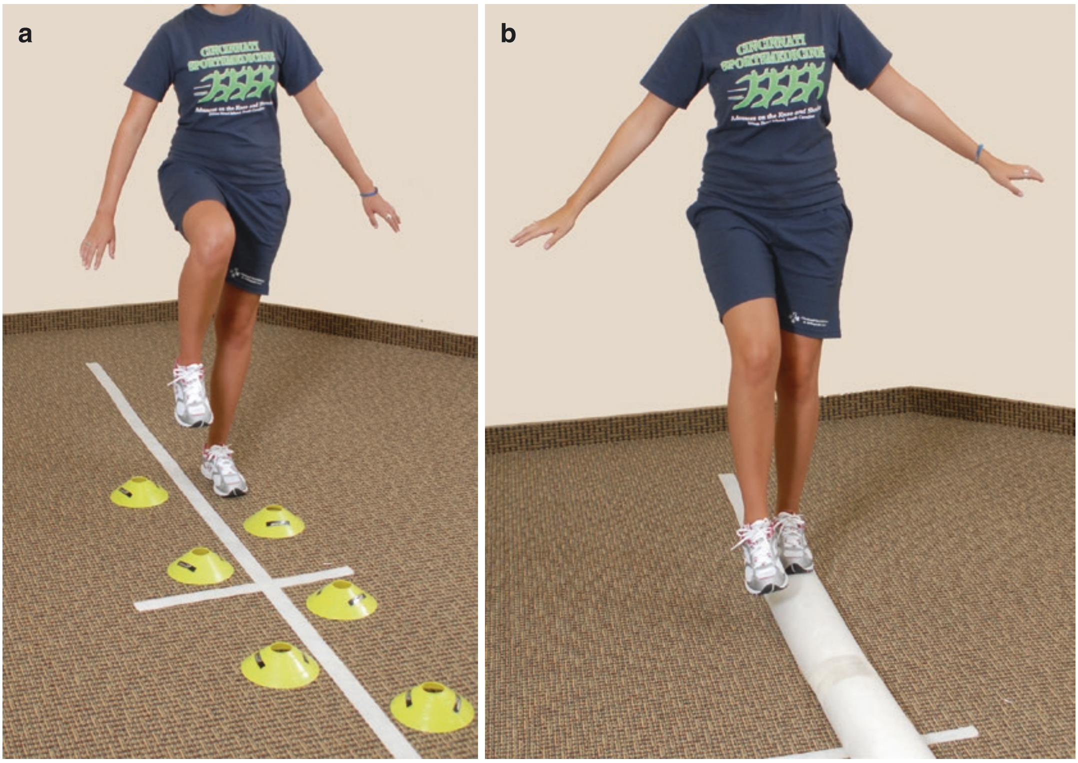


Fig. 8.5 Gait retraining and balance exercises includes walking (**a**) over cups or cones and (**b**) on half foam rolls. (Reprinted from Heckmann et al. [65])

recover balance and dynamic muscular control required to maintain an upright position and be able to walk from one end of the roll to the other. Balance exercises are progressed from single-leg stance on a level surface to single-leg stance on an unstable surface such as a mini-trampoline or unstable platform in order to promote greater dynamic limb control (Fig. 8.7). To provide a greater challenge, patients may assume the single-leg stance position and throw and catch a weighted ball against an inverted mini-trampoline until fatigue occurs. Developing a center of balance, limb symmetry, quadriceps control in mid-stance, and postural positioning are benefits obtained from these training methods.

Perturbation training techniques are begun during Phase 3 to further promote balance and neuromuscular control. The therapist stands behind the patient who is on a rocker board and disrupts their body posture, position, and the platform periodically to enhance dynamic knee stability (Fig. 8.8). Patients may begin in double-leg stance and progress to single-limb stance.

8.3 Clinical Studies

Multiple studies have documented the advantages of formal preoperative rehabilitation in terms of improvements in ROM, muscle strength, and neuromuscular function [12–16]. Failla et al. [12] reported the effectiveness of a preoperative rehabilitation program (5 weeks, 10 clinic visits for neuromuscular training) as measured with the International Knee Documentation Committee (IKDC) subjective knee form and Knee Injury

Fig. 8.6 Walking with exaggerated hip flexion may be done with or without a resistance band. (Reprinted from Heckmann et al. [65])

and Osteoarthritis Outcome Score (KOOS). After completion of the preoperative program (and before surgery), the 148 patients that participated had significant improvements in the IKDC score (from 70 ± 13 to 77 ± 13, $P < 0.001$), which were significantly greater than a group of 1994 patients that did not participate (mean, 50 ± 17 points; $P < 0.001$). Two years after ACL reconstruction, the patients in the experimental group continued to have significantly higher IKDC scores compared with controls (84 ± 25 vs 72 ± 32 points, respectively; $P < 0.001$). KOOS scores for all subscales were significantly higher in the experimental group at both baseline and follow-up (i.e., pain at follow-up: 94 ± 10 vs 78 ± 33, respectively; $P = 0.004$). A significantly greater percentage of patients in the experimental group returned to preinjury sports (72% vs 63%, respectively; $P < 0.001$).

Shaarani et al. [14] randomized 20 patients waiting ACL reconstruction to a preoperative rehabilitation exercise or control (no exercise) group. The preoperative program consisted of supervised resistance training and balancing exercises for 6 weeks. Compared with baseline (first office visit) values, patients in the preoperative program had significantly improved quadriceps peak torque (at 90°/s), quadriceps cross-sectional area ($P = 0.001$), distance hopped in the single-leg hop test ($P = 0.001$), and modified Cincinnati Knee Rating scores ($P = 0.004$) measured before surgery. Patients in the control group did not have significant differences in these values from baseline to the preoperative visit. At 12 weeks post ACL reconstruction, patients who participated in the preoperative program had significantly greater hop distances ($P = 0.001$) and modified Cincinnati Knee Rating scores ($P = 0.004$) than controls. The mean time to return to sport was 42.5 weeks for the control group and 34.2 weeks for the exercise group ($P = 0.055$). No further measurements were obtained after 12 weeks postoperative.

Eitzen et al. [15] examined the effectiveness of a 5-week, 10-session preoperative rehabilitation program in 100 patients who had sustained acute ACL ruptures. The program included intensive muscle strength training, plyometrics, proprioception, balance, and neuromuscular exercises. Upon completion of the program, significant improvements were found in quadriceps and hamstrings peak torque ($P < 0.05$; percent change range, 8.2–12.9%; standardized response means range, 0.49–0.60). Significant improvements were found in two single-leg hop tests (triple hop and timed hop; $P < 0.05$) and in the IKDC-2000 score (from 69.7 ± 11.7 to 77.2 ± 10.2; $P < 0.001$). The authors concluded that the program was well tolerated (symptoms occurred in only 3.4%) and could be used to either improve knee function before ACL reconstruction or as an initial step in nonoperative treatment.

Fig. 8.7 Single-leg balance exercises done on (**a**, **b**) unstable platforms and (**c**) including the patient throwing and catching a weighted ball against an inverted mini-trampoline. (Reprinted from Heckmann et al. [65])

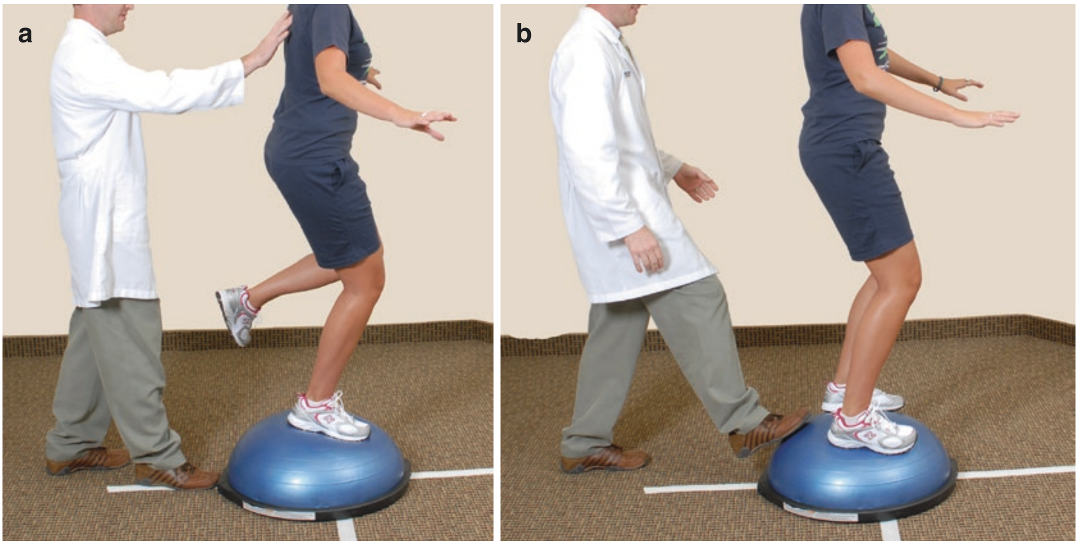


Fig. 8.8 Perturbation training performed by using direct contact with either the (**a**) patient or (**b**) platform. (Reprinted from Heckmann et al. [65])

References

1. Eitzen I, Holm I, Risberg MA. Preoperative quadriceps strength is a significant predictor of knee function two years after anterior cruciate ligament reconstruction. Br J Sports Med. 2009;43(5):371–6. https://doi.org/10.1136/bjsm.2008.057059.
2. Shelbourne KD, Wilckens JH, Mollabashy A, DeCarlo M. Arthrofibrosis in acute anterior cruciate ligament reconstruction. The effect of timing of reconstruction and rehabilitation. Am J Sports Med. 1991;19(4):332–6.
3. Mauro CS, Irrgang JJ, Williams BA, Harner CD. Loss of extension following anterior cruciate ligament reconstruction: analysis of incidence and etiology using IKDC criteria. Arthroscopy. 2008;24(2):146–53. https://doi.org/10.1016/j.arthro.2007.08.026.
4. Mohtadi NG, Webster-Bogaert S, Fowler PJ. Limitation of motion following anterior cruciate ligament reconstruction. A case-control study. Am J Sports Med. 1991;19(6):620–4; discussion 624-625.
5. Wasilewski SA, Covall DJ, Cohen S. Effect of surgical timing on recovery and associated injuries after anterior cruciate ligament reconstruction. Am J Sports Med. 1993;21(3):338–42.
6. de Valk EJ, Moen MH, Winters M, Bakker EW, Tamminga R, van der Hoeven H. Preoperative patient and injury factors of successful rehabilitation after anterior cruciate ligament reconstruction with single-bundle techniques. Arthroscopy. 2013;29(11):1879–95. https://doi.org/10.1016/j.arthro.2013.07.273.
7. Noyes FR, Barber-Westin SD. Meniscus tears: diagnosis, repair techniques, and clinical outcomes. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes, chap. 23, 2nd ed. Philadelphia: Elsevier; 2017, p. 677–718. https://doi.org/10.1016/B978-0-323-32903-3.00023-8.
8. Noyes FR, Barber-Westin SD. Posterior cruciate ligament injuries: diagnosis, operative techniques, and clinical outcomes. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes, chap. 16, 2nd ed. Philadelphia: Elsevier; 2017, p. 447–526. https://doi.org/10.1016/B978-0-323-32903-3.00016-0.
9. Noyes FR, Barber-Westin SD. Posterolateral ligament injuries: diagnosis, operative techniques, and clinical outcomes. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes, chap. 17, 2nd ed. Philadelphia: Elsevier; 2017, p. 527–77. https://doi.org/10.1016/B978-0-323-32903-3.00017-2.
10. Noyes FR, Barber-Westin SD. Medial and posteromedial ligament injuries: diagnosis, operative techniques, and clinical outcomes. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes, chap. 19, 2nd ed. Philadelphia: Elsevier; 2017, p. 608–35. https://doi.org/10.1016/B978-0-323-32903-3.00019-6.
11. Alshewaier S, Yeowell G, Fatoye F. The effectiveness of pre-operative exercise physiotherapy rehabilitation on the outcomes of treatment following anterior cruciate ligament injury: a systematic review. Clin Rehabil. 2017;31(1):34–44. https://doi.org/10.1177/0269215516628617.
12. Failla MJ, Logerstedt DS, Grindem H, Axe MJ, Risberg MA, Engebretsen L, Huston LJ, Spindler KP, Snyder-Mackler L. Does extended preoperative rehabilitation influence outcomes 2 years after ACL reconstruction? A comparative effectiveness study between the MOON and Delaware-Oslo ACL cohorts.

Am J Sports Med. 2016;44(10):2608–14. https://doi.org/10.1177/0363546516652594.
13. Logerstedt D, Lynch A, Axe MJ, Snyder-Mackler L. Pre-operative quadriceps strength predicts IKDC 2000 scores 6 months after anterior cruciate ligament reconstruction. Knee. 2013;20(3):208–12. https://doi.org/10.1016/j.knee.2012.07.011.
14. Shaarani SR, O'Hare C, Quinn A, Moyna N, Moran R, O'Byrne JM. Effect of prehabilitation on the outcome of anterior cruciate ligament reconstruction. Am J Sports Med. 2013;41(9):2117–27. https://doi.org/10.1177/0363546513493594.
15. Eitzen I, Moksnes H, Snyder-Mackler L, Risberg MA. A progressive 5-week exercise therapy program leads to significant improvement in knee function early after anterior cruciate ligament injury. J Orthop Sports Phys Ther. 2010;40(11):705–21. https://doi.org/10.2519/jospt.2010.3345.
16. Grindem H, Granan LP, Risberg MA, Engebretsen L, Snyder-Mackler L, Eitzen I. How does a combined preoperative and postoperative rehabilitation programme influence the outcome of ACL reconstruction 2 years after surgery? A comparison between patients in the Delaware-Oslo ACL cohort and the Norwegian National Knee Ligament Registry. Br J Sports Med. 2015;49(6):385–9. https://doi.org/10.1136/bjsports-2014-093891.
17. Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: graft options and clinical outcomes. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes, chap. 8, 2nd ed. Philadelphia: Elsevier; 2017, p. 221–57. https://doi.org/10.1016/B978-0-323-32903-3.00008-1.
18. Christino MA, Fantry AJ, Vopat BG. Psychological aspects of recovery following anterior cruciate ligament reconstruction. J Am Acad Orthop Surg. 2015;23(8):501–9. https://doi.org/10.5435/JAAOS-D-14-00173.
19. Coronado RA, Bird ML, Van Hoy EE, Huston LJ, Spindler KP, Archer KR. Do psychosocial interventions improve rehabilitation outcomes after anterior cruciate ligament reconstruction? A systematic review. Clin Rehabil. 2018;32(3):287–98. https://doi.org/10.1177/0269215517728562.
20. Noyes FR, Bassett RW, Grood ES, Butler DL. Arthroscopy in acute traumatic hemarthrosis of the knee. Incidence of anterior cruciate tears and other injuries. J Bone Joint Surg Am. 1980;62(5):687–95, 757.
21. Wang JH, Lee JH, Cho Y, Shin JM, Lee BH. Efficacy of knee joint aspiration in patients with acute ACL injury in the emergency department. Injury. 2016;47(8):1744–9. https://doi.org/10.1016/j.injury.2016.05.025.
22. Palmieri-Smith RM, Kreinbrink J, Ashton-Miller JA, Wojtys EM. Quadriceps inhibition induced by an experimental knee joint effusion affects knee joint mechanics during a single-legged drop landing. Am J Sports Med. 2007;35(8):1269–75.
23. Torry MR, Decker MJ, Millett PJ, Steadman JR, Sterett WI. The effects of knee joint effusion on quadriceps electromyography during jogging. J Sports Sci Med. 2005;4:1–8.
24. Cosgarea AJ, Sebastianelli WJ, DeHaven KE. Prevention of arthrofibrosis after anterior cruciate ligament reconstruction using the central third patellar tendon autograft. Am J Sports Med. 1995;23(1):87–92.
25. Meighan AA, Keating JF, Will E. Outcome after reconstruction of the anterior cruciate ligament in athletic patients. A comparison of early versus delayed surgery. J Bone Joint Surg Br. 2003;85(4):521–4.
26. Shelbourne KD, Johnson GE. Outpatient surgical management of arthrofibrosis after anterior cruciate ligament surgery. Am J Sports Med. 1994;22(2):192–7.
27. Strum GM, Friedman MJ, Fox JM, Ferkel RD, Dorey FH, Del Pizzo W, Snyder SJ. Acute anterior cruciate ligament reconstruction. Analysis of complications. Clin Orthop Relat Res. 1990; (253):184–9.
28. Shelbourne KD, Foulk DA. Timing of surgery in acute anterior cruciate ligament tears on the return of quadriceps muscle strength after reconstruction using an autogenous patellar tendon graft. Am J Sports Med. 1995;23(6):686–9.
29. Bach BR, Jones GT, Sweet FA, Hager CA. Arthroscopy-assisted anterior cruciate ligament reconstruction using patellar tendon substitution. Two- to four-year follow-up results. Am J Sports Med. 1994;22:758–67.
30. Wilk KE, Macrina LC, Cain EL, Dugas JR, Andrews JR. Recent advances in the rehabilitation of anterior cruciate ligament injuries. J Orthop Sports Phys Ther. 2012;42(3):153–71. https://doi.org/10.2519/jospt.2012.3741.
31. Culvenor AG, Lai CC, Gabbe BJ, Makdissi M, Collins NJ, Vicenzino B, Morris HG, Crossley KM. Patellofemoral osteoarthritis is prevalent and associated with worse symptoms and function after hamstring tendon autograft ACL reconstruction. Br J Sports Med. 2014;48(6):435–9. https://doi.org/10.1136/bjsports-2013-092975.
32. Neuman P, Kostogiannis I, Friden T, Roos H, Dahlberg LE, Englund M. Patellofemoral osteoarthritis 15 years after anterior cruciate ligament injury—a prospective cohort study. Osteoarthr Cartil. 2009;17(3):284–90. https://doi.org/10.1016/j.joca.2008.07.005.
33. Shelbourne KD, Urch SE, Gray T, Freeman H. Loss of normal knee motion after anterior cruciate ligament reconstruction is associated with radiographic arthritic changes after surgery. Am J Sports Med. 2012;40(1):108–13. https://doi.org/10.1177/0363546511423639.
34. Hasegawa S, Kobayashi M, Arai R, Tamaki A, Nakamura T, Moritani T. Effect of early implementation of electrical muscle stimulation to prevent muscle atrophy and weakness in patients after anterior cruciate ligament reconstruction. J Electromyogr Kinesiol. 2011;21(4):622–30. https://doi.org/10.1016/j.jelekin.2011.01.005.

35. Imoto AM, Peccin S, Almeida GJ, Saconato H, Atallah AN. Effectiveness of electrical stimulation on rehabilitation after ligament and meniscal injuries: a systematic review. Sao Paulo Med J. 2011;129(6):414–23.
36. Feil S, Newell J, Minogue C, Paessler HH. The effectiveness of supplementing a standard rehabilitation program with superimposed neuromuscular electrical stimulation after anterior cruciate ligament reconstruction: a prospective, randomized, single-blind study. Am J Sports Med. 2011;39(6):1238–47. https://doi.org/10.1177/0363546510396180.
37. Snyder-Mackler L, Ladin Z, Schepsis AA, Young JC. Electrical stimulation of the thigh muscles after reconstruction of the anterior cruciate ligament. Effects of electrically elicited contraction of the quadriceps femoris and hamstring muscles on gait and on strength of the thigh muscles. J Bone Joint Surg Am. 1991;73(7):1025–36.
38. Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. A prospective, randomized clinical trial of electrical stimulation. J Bone Joint Surg Am. 1995;77(8):1166–73.
39. Wright RW, Preston E, Fleming BC, Amendola A, Andrish JT, Bergfeld JA, Dunn WR, Kaeding C, Kuhn JE, Marx RG, McCarty EC, Parker RC, Spindler KP, Wolcott M, Wolf BR, Williams GN. A systematic review of anterior cruciate ligament reconstruction rehabilitation: part II: open versus closed kinetic chain exercises, neuromuscular electrical stimulation, accelerated rehabilitation, and miscellaneous topics. J Knee Surg. 2008;21(3):225–34.
40. Perry MC, Morrissey MC, King JB, Morrissey D, Earnshaw P. Effects of closed versus open kinetic chain knee extensor resistance training on knee laxity and leg function in patients during the 8- to 14-week post-operative period after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2005;13(5):357–69.
41. Beynnon BD, Uh BS, Johnson RJ, Abate JA, Nichols CE, Fleming BC, Poole AR, Roos H. Rehabilitation after anterior cruciate ligament reconstruction. A prospective, randomized, double-blind comparison of programs administered over 2 different time periods. Am J Sports Med. 2005;33(3):347–59.
42. Isberg J, Faxen E, Brandsson S, Eriksson BI, Karrholm J, Karlsson J. Early active extension after anterior cruciate ligament reconstruction does not result in increased laxity of the knee. Knee Surg Sports Traumatol Arthrosc. 2006;14(11):1108–15. https://doi.org/10.1007/s00167-006-0138-2.
43. Beynnon BD, Johnson RJ, Naud S, Fleming BC, Abate JA, Brattbakk B, Nichols CE. Accelerated versus nonaccelerated rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind investigation evaluating knee joint laxity using roentgen stereophotogrammetric analysis. Am J Sports Med. 2011;39(12):2536–48. https://doi.org/10.1177/0363546511422349.
44. Fukuda TY, Fingerhut D, Moreira VC, Camarini PM, Scodeller NF, Duarte A Jr, Martinelli M, Bryk FF. Open kinetic chain exercises in a restricted range of motion after anterior cruciate ligament reconstruction: a randomized controlled clinical trial. Am J Sports Med. 2013;41(4):788–94. https://doi.org/10.1177/0363546513476482.
45. Tagesson S, Oberg B, Good L, Kvist J. A comprehensive rehabilitation program with quadriceps strengthening in closed versus open kinetic chain exercise in patients with anterior cruciate ligament deficiency: a randomized clinical trial evaluating dynamic tibial translation and muscle function. Am J Sports Med. 2008;36(2):298–307.
46. Ohkoshi Y, Yasuda K, Kaneda K, Wada T, Yamanaka M. Biomechanical analysis of rehabilitation in the standing position. Am J Sports Med. 1991;19(6):605–11.
47. Kulas AS, Hortobagyi T, DeVita P. Trunk position modulates anterior cruciate ligament forces and strains during a single-leg squat. Clin Biomech (Bristol, Avon). 2012;27(1):16–21. https://doi.org/10.1016/j.clinbiomech.2011.07.009.
48. Denti M, Randelli P, Lo Vetere D, Moioli M, Bagnoli I, Cawley PW. Motor control performance in the lower extremity: normals vs. anterior cruciate ligament reconstructed knees 5-8 years from the index surgery. Knee Surg Sports Traumatol Arthrosc. 2000;8(5):296–300.
49. Yosmaoglu HB, Baltaci G, Kaya D, Ozer H. Tracking ability, motor coordination, and functional determinants after anterior cruciate ligament reconstruction. J Sport Rehabil. 2011;20(2):207–18.
50. Zouita Ben Moussa A, Zouita S, Dziri C, Ben Salah FZ. Single-leg assessment of postural stability and knee functional outcome two years after anterior cruciate ligament reconstruction. Ann Phys Rehabil Med. 2009;52(6):475–84. https://doi.org/10.1016/j.rehab.2009.02.006.
51. Hooks TR, Wilk KE, Reinold MM. Comparison of proprioceptive deficits of the involved and noninvolved lower extremity following ACL injury and surgical reconstruction. J Orthop Sports Phys Ther. 2003;33:A59.
52. Fremerey RW, Lobenhoffer P, Zeichen J, Skutek M, Bosch U, Tscherne H. Proprioception after rehabilitation and reconstruction in knees with deficiency of the anterior cruciate ligament: a prospective, longitudinal study. J Bone Joint Surg Br. 2000;82(6):801–6.
53. Dutton M. Neuromuscular control. In: Dutton M, editor. Orthopaedic examination, evaluation and intervention. New York: McGraw Hill; 2004. p. 55–7.
54. Wojtys EM, Huston LJ. Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities. Am J Sports Med. 1994;22(1):89–104.

55. Magyar MO, Knoll Z, Kiss RM. Effect of medial meniscus tear and partial meniscectomy on balancing capacity in response to sudden unidirectional perturbation. J Electromyogr Kinesiol. 2012;22(3):440–5. https://doi.org/10.1016/j.jelekin.2012.01.010.
56. Malliou P, Gioftsidou A, Pafis G, Rokka S, Kofotolis N, Mavromoustakos S, Godolias G. Proprioception and functional deficits of partial meniscectomized knees. Eur J Phys Rehabil Med. 2012;48(2):231–6.
57. Muaidi QI, Nicholson LL, Refshauge KM, Adams RD, Roe JP. Effect of anterior cruciate ligament injury and reconstruction on proprioceptive acuity of knee rotation in the transverse plane. Am J Sports Med. 2009;37(8):1618–26. https://doi.org/10.1177/0363546509332429.
58. Goetschius J, Kuenze CM, Saliba S, Hart JM. Reposition acuity and postural control after exercise in anterior cruciate ligament reconstructed knees. Med Sci Sports Exerc. 2013;45(12):2314–21. https://doi.org/10.1249/MSS.0b013e31829bc6ae.
59. Alonso AC, Greve JM, Camanho GL. Evaluating the center of gravity of dislocations in soccer players with and without reconstruction of the anterior cruciate ligament using a balance platform. Clinics (Sao Paulo). 2009;64(3):163–70.
60. Morgan MD, Salmon LJ, Waller A, Roe JP, Pinczewski LA. Fifteen-year survival of endoscopic anterior cruciate ligament reconstruction in patients aged 18 years and younger. Am J Sports Med. 2016;44(2):384–92. https://doi.org/10.1177/0363546515623032.
61. Kamath GV, Murphy T, Creighton RA, Viradia N, Taft TN, Spang JT. Anterior cruciate ligament injury, return to play, and reinjury in the elite collegiate athlete: analysis of an NCAA Division I cohort. Am J Sports Med. 2014;42(7):1638–43. https://doi.org/10.1177/0363546514524164.
62. Thompson SM, Salmon LJ, Waller A, Linklater J, Roe JP, Pinczewski LA. Twenty-year outcome of a longitudinal prospective evaluation of isolated endoscopic anterior cruciate ligament reconstruction with patellar tendon or hamstring autograft. Am J Sports Med. 2016;44(12):3083–94. https://doi.org/10.1177/0363546516658041.
63. Pinczewski LA, Lyman J, Salmon LJ, Russell VJ, Roe J, Linklater J. A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: a controlled, prospective trial. Am J Sports Med. 2007;35(4):564–74.
64. Noyes FR, Barber-Westin SD. Prevention and treatment of knee arthrofibrosis. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 1059–102.
65. Heckmann TP, Noyes FR, Barber-Westin SD. Rehabilitation after ACL reconstruction. In: ACL injuries in the female athlete. Causes, impacts, and conditioning programs. 2nd ed. New York: Springer; 2018. p. 505–36.

9 Extended Preoperative Rehabilitation: Does It Influence Return to Sport After Surgery?

Elanna K. Arhos, Jacob J. Capin, May Arna Risberg, and Lynn Snyder-Mackler

9.1 Introduction

Preoperative rehabilitation for anterior cruciate ligament reconstruction (ACLR) typically stops once impairments are resolved prior to surgery. Clinician-scientists from the Delaware-Oslo cohort (DOC) operationally define extended preoperative rehabilitation, or "prehabilitation," as a period of training sessions that focus on neuromuscular training (i.e., perturbation training), progressive strengthening, and plyometric and agility training. The intent of this program is to maximize function of the injured knee, as preoperative function directly influences the status of the knee joint after surgery. The DOC has spent more than a decade developing and evaluating outcomes of extended, evidence-based preoperative rehabilitation programs.

For over a decade, we have been conducting a binational, ongoing prospective cohort study of patients with anterior cruciate ligament (ACL) injuries who undergo extended preoperative rehabilitation [1–4]. During this preoperative rehabilitation period, patients are classified as potential copers (those who demonstrate dynamic knee stability and good knee function) or noncopers (those who demonstrate instability and poor knee function) [5]. The DOC consists of a Norwegian arm at Oslo University Hospital and a US arm at the University of Delaware. Prior to the DOC, there was little research to assess the effects of extended preoperative rehabilitation on outcomes after outcomes after ACLR [6].

Preoperative rehabilitation is common practice at clinics affiliated with both the University of Delaware and the Oslo University Hospital. We encourage patients to undergo extended progressive rehabilitation before moving forward with decision making regarding operative versus nonoperative injury management. Clinicians and researchers from our groups have been advocating internationally for years for the use of extended preoperative rehabilitation as standard of care. Implementing extended preoperative rehabilitation as part of the plan of care early after ACL injury, clinicians can counsel patients

E. K. Arhos
Biomechanics and Movement Science Program, University of Delaware, Newark, DE, USA
e-mail: earhos@udel.edu

J. J. Capin · L. Snyder-Mackler (✉)
Biomechanics and Movement Science Program, University of Delaware, Newark, DE, USA

Department of Physical Therapy, University of Delaware, Newark, DE, USA
e-mail: capin@udel.edu; smack@udel.edu

M. A. Risberg
Norwegian Research Center for Active Rehabilitation, Department of Sports Medicine, Norwegian School of Sport Sciences, Oslo, Norway

Norwegian Research Center for Active Rehabilitation, Department of Orthopaedics, Oslo University Hospital, Oslo, Norway
e-mail: m.a.risberg@nih.no

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_9

and their families about outcomes, identify if athletes require surgery, and improve both copers' and noncopers' post-surgical outcomes. There are many benefits to preoperative rehabilitation that positively influence an athlete's outcomes after surgery [4]. When combined with time frames for healing and criterion-based postoperative rehabilitation, extended preoperative rehabilitation leads to better patient-reported outcomes, function, and return to sport (RTS) rates [1–3]. This chapter will describe the evidence-based components to a successful extended preoperative rehabilitation program and our outcomes, along with criterion-based postoperative rehabilitation programs and RTS criteria.

9.2 Background

9.2.1 Preoperative Milestones

Impairments must be resolved first. We recommend entering surgery with a "quiet knee," including little to no effusion [7] or pain, full knee range of motion (ROM), no obvious gait impairments, and ≥70% quadriceps strength index (QI) (further explained in Sect. 9.5). Once patients and clinicians have achieved a quiet knee, often termed "clinical impairment resolution", they should initiate preoperative progressive strengthening. Patients also complete 10 preoperative training sessions (at least 2×/week) that encompass neuromuscular training (i.e., perturbation training), strengthening, and plyometric and agility training [8].

9.2.2 Importance of Quadriceps Strength

Preoperative rehabilitation conceptually draws from focused strengthening of the quadriceps prior to surgery. Preoperative quadriceps muscle strength is positively correlated to short-term function after ACLR [9, 10]. Patients who enter ACLR with strong quadriceps strength do better after surgery than those who have weaker quadriceps strength [10]. This evidence underscores the importance of strengthening the quadriceps prior to ACLR, and we suggest that ACLR not be performed until quadriceps muscle strength is at least 80% of that of the uninvolved limb. Quadriceps strengthening is thus an essential component of a successful preoperative rehabilitation protocol. Preoperative quadriceps strength predicts International Knee Committee Documentation 2000 (IKDC 2000) scores 6 months after ACLR [9]. These data further support the notion that higher preoperative quadriceps strength results in better knee function postoperatively. Extended rehabilitation may be necessary to restore sufficient quadriceps strength and promote superior long-term outcomes.

9.2.3 Evidence for Preoperative Rehabilitation

The DOC has dedicated significant time and efforts into investigating the addition of progressive strengthening and neuromuscular training to preoperative rehabilitation programs, and the effects of extended preoperative rehabilitation on strength, function, patient-reported outcomes, and RTS rates. Prior to the DOC, there was limited research looking at the effects of evidence-based protocols before ACLR. The progressive preoperative rehabilitation program our patients follow commences after clinical impairment resolution, with the goal of optimizing knee function prior to ACLR [4]. Implementation of this rehabilitation program leads to significantly improved knee function early after ACL injury, including stronger quadriceps and hamstring muscles, function, and patient-reported knee function, and highlights the importance of including a period of high-intensity exercise prior to surgery [4].

During the preoperative rehabilitation program, we classify patients as potential copers or noncopers. From here, patients make the decision to undergo ACLR or to pursue nonoperative management. Classification as a potential coper, with dynamic knee stability, may play a role in patients choosing nonoperative injury management. Recent data from our group suggests that extended preoperative rehabilitation may allow patients who would typically undergo ACLR after initial classification as a noncoper the opportunity to determine if they are potential copers after extended rehabilitation. After a 10-session preoperative rehabilitation program, 44% of athletes who were initially classified as noncopers changed to potential copers, while only 13% of athletes changed from potential copers to noncopers [11]. These data highlight the importance of progressive preoperative rehabilitation in the possible prevention of surgery, and in enhancing optimal long-term knee function.

9.3 Evidence-Based Preoperative Rehabilitation Interventions

Preoperative rehabilitation programs must incorporate components of progressive strength training, agility and plyometric training, and neuromuscular re-education to maximize the athlete's preoperative function. Programs with more than one component (e.g., agility and strength) result in ACL injury risk reduction and we advocate for multimodal programs for preoperative rehabilitation [12]. While it is not necessary to follow our exact program (detailed in Sect. 8.3), it is essential that clinicians incorporate all of the described elements (neuromuscular training, strength, agility) for a comprehensive preoperative rehabilitation program.

9.3.1 Perturbation Training

Perturbation training, a neuromuscular training program, consists of a series of 10 sessions incorporating balance and proprioceptive training [4, 8]. Perturbation training includes exercises performed on roller boards, rocker boards, and platforms. Patients begin in double-limb support on platforms and progress to single-limb support, first on the rocker board, and eventually the roller board (Figs. 9.1 and 9.2) We apply perturbations to the support surface of the injured limb in medial/lateral and anterior/posterior directions, and progress to diagonal and rotational movements. As perturbation training sessions progress, the intensity, magnitude, and speed of the perturbations increase to match sport-specific demands [8]. Data from primary ACL injury prevention is also relevant here and emphasizes the importance of a multi-component program including progressive strength and agility training [11].

Several studies have discussed the benefits of preoperative rehabilitation with perturbation training versus preoperative rehabilitation alone [8, 13, 14]. Perturbation training improves coordinated muscle activity, allowing patients to maintain functional status for longer periods of time [8, 15]. Sessions should include stability training and balance in a controlled environment so that the involved knee is re-introduced to multi-directional forces and torques. The perturbation training session guidelines from the University of Delaware are published and accessible [15] and are presented in Table 9.1.

9.3.2 Progressive Strength Training

Preoperative strength training should focus on progressive strengthening of the quadriceps and hamstrings, with a goal of achieving 80% quadriceps and hamstring strength prior to surgery [3]. Clinicians should encourage both open and closed kinetic chain strengthening exercises, as well as unilateral and bilateral lower extremity training [16–19]. We recommend the use of heavy resistance strength training to improve neuromuscular activation and increase strength in the preoperative time period. Joint soreness should be distinguished from muscle soreness throughout the progressive strength training period and should be monitored, and exercise modified, based on soreness rules (Table 9.2) [20, 21].

9.3.3 Agility and Plyometric Training

Agility training is included to target neuromuscular control (dynamic stability) and muscle

Fig. 9.1 Perturbation training progression from double-limb support with right lower extremity on a platform and left lower extremity on a roller board (**a**), to single-limb support on one roller board (**b**), to single-limb support on a rocker board (**c**)

strength during specific activities and consists of double- and single-limb plyometric exercises. Developing proper alignment during exercises is critical. Clinicians should ensure that athletes maintain a neutral (frontal plane) alignment and use a flexed, rather than stiff, knee during landing [22]. We suggest a goal of achieving 90% LSI on hop test performance prior to surgery [23]. Hop testing, further described in Sect. 8.5, allows clinicians to assess inter-limb asymmetry and functional performance. Inter-limb asymmetries are common early after ACL injury and reconstruction, and can persist up to several years [24, 25]. Restoring movement symmetry is critical in returning athletes to play and preventing reinjury [26, 27]. Common strength and agility exercises that are included in our program are presented in Table 9.3. In the Clinical Practice Guidelines (CPG) for Exercise-Based Knee and Anterior Cruciate Ligament Injury

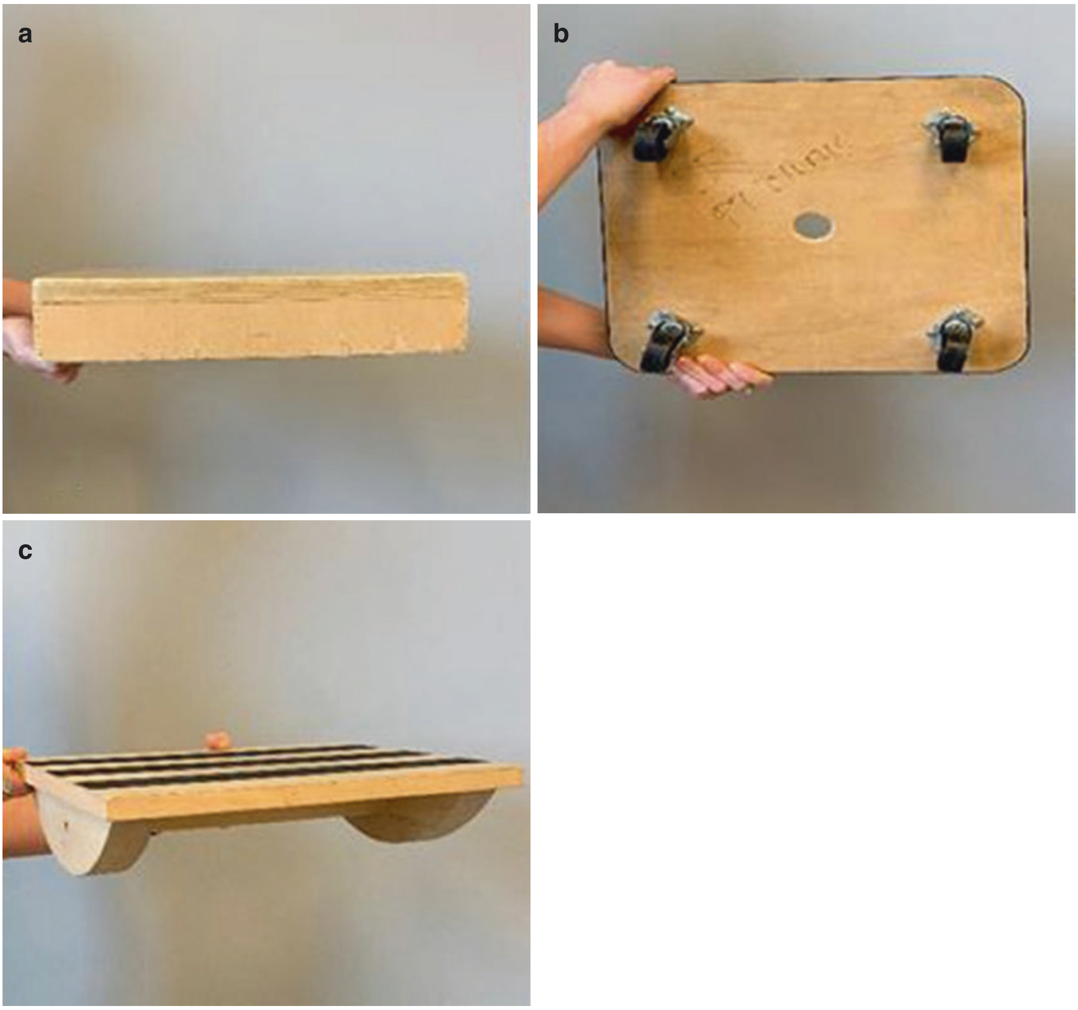


Fig. 9.2 (**a**) Platform, (**b**) roller board, (**c**) rocker board

Prevention [12], Arundale et al. determined that programs that incorporate plyometric and strengthening components are more effective than those without both of these components in reducing ACL injuries in women [28–30]. While this CPG is focused on injury prevention, it points to the importance of multiple components in both optimal lower extremity and ACL-specific rehabilitation. Secondary prevention should be a part of a rehabilitation program to reduce the risk of new injuries in these individuals [31]. Further detail on many exercise programs and their content can be found in the CPG, as well as the many evidenced-based injury prevention programs on which the CPG is based [12].

9.4 Postoperative Criterion-Based Rehabilitation

Successful RTS is dependent on successful preoperative rehabilitation and implementation of evidence-based postoperative rehabilitation. Criterion-based rehabilitation programs, typically divided into three phases followed by a RTS training phase [21, 32–36], should be implemented. In the early postoperative rehabilitation, the focus is on early activation of the quadriceps, normalizing gait patterns, and restoring full and symmetric knee ROM, particularly extension ROM. Enhancing full functional strength of the quadriceps is done with the addition of high-intensity neuromuscular electrical stimulation

Table 9.1 Perturbation training protocol[a]

Sessions 1–4. Early phase			
Progression by adding perturbations in all directions and minimizing of verbal cues			
Session	Rocker board	Roller board/Platform	Roller board
1	• Bilateral stance • 2 sets, anterior/posterior • 2 sets, medial/lateral	• 2 sets with injured limb on roller board, anterior/posterior • 2 sets with uninvolved limb on roller board, anterior/posterior	• Bilateral stance • 2 sets anterior/posterior
2	• Unilateral stance • 2 sets anterior/posterior direction • 2 sets medial/lateral direction	• 2 sets with injured limb on roller board, anterior/posterior plus medial/lateral • 2 sets with uninvolved limb on roller board, anterior/posterior plus medial/lateral	• Unilateral stance • 2 sets anterior/posterior
3	• Unilateral stance • 2 sets medial/lateral direction • 2 sets diagonal direction	• 2 sets with injured limb on roller board, anterior/posterior plus medial/lateral plus rotation • 2 sets with uninvolved limb on roller board, anterior/posterior plus medial/lateral plus rotation	• Unilateral stance • 2 sets anterior/posterior plus medial/lateral
4	• Unilateral stance • 2 sets medial/lateral direction • 2 sets diagonal direction	• 2 sets with injured limb on roller board, anterior/posterior plus medial/lateral plus rotation • 2 sets with uninvolved limb on roller board, anterior/posterior plus medial/lateral plus rotation	• Unilateral stance • 2 sets anterior/posterior plus medial/lateral plus rotation
Sessions 5–7: Middle phase			
Progression by adding light sport-specific activity during perturbations			
Session	Rocker board	Roller board/Platform	Roller board
5	• Unilateral stance • 2 sets anterior/posterior direction • 2 sets medial/lateral direction • 2 sets diagonal direction • Ball against wall	• 2 sets with injured limb on roller board, anterior/posterior plus medial/lateral plus rotation • 2 sets with uninvolved limb on roller board, anterior/posterior plus medial/lateral plus rotation • Ball against wall	• Unilateral stance • 2 sets anterior/posterior plus medial/lateral plus rotation • Ball against wall
6	• Unilateral stance • 2 sets anterior/posterior direction • 2 sets medial/lateral direction • 2 sets diagonal direction • Ball against wall/floor	• 2 sets with injured limb on roller board, anterior/posterior plus medial/lateral • 2 sets with uninvolved limb on roller board, anterior/posterior plus medial/lateral • Ball against wall/floor	• Unilateral stance • 2 sets anterior/posterior plus medial/lateral plus rotation • Ball against wall/floor
7	• Unilateral stance • 2 sets medial/lateral direction • 2 sets diagonal direction • Ball thrown by other	• 2 sets with injured limb on roller board, anterior/posterior plus medial/lateral • 2 sets with uninvolved limb on roller board, anterior/posterior plus medial/lateral • Ball thrown by other	• Unilateral stance • 2 sets anterior/posterior plus medial/lateral plus rotation • Ball thrown by other

Table 9.1 (continued)

Sessions 8–10: Late phase			
Progression by adding sport-specific stances combined with sport-specific activity			
Session	Rocker board	Roller board/Platform	Roller board
8	• Unilateral stance • 2 sets anterior/posterior direction • 2 sets medial/lateral direction • 2 sets diagonal direction • Ball against wall/floor, thrown by other • Other individually adjusted relevant sport-specific activities	• 2 sets with injured limb on roller board, anterior/posterior plus medial/lateral plus rotation • 2 sets with uninvolved limb on roller board, anterior/posterior plus medial/lateral plus rotation • Ball against wall/floor, thrown by other • Other individually adjusted relevant sport-specific activities	• Unilateral stance • 2 sets anterior/posterior plus medial/lateral plus rotation • Ball against wall/floor, thrown by other • Other individually adjusted relevant sport-specific activities
9	• Unilateral stance • 2 sets medial/lateral direction • 2 sets diagonal direction • Ball against wall/floor, thrown by other • Other individually adjusted relevant sport-specific activities	• 2 sets with injured limb on roller board, anterior/posterior plus medial/lateral plus rotation • 2 sets with uninvolved limb on roller board, anterior/posterior plus medial/lateral plus rotation • Ball against wall/floor, thrown by other • Other individually adjusted relevant sport-specific activities	• Unilateral stance • 2 sets anterior/posterior plus medial/lateral plus rotation • Ball against wall/floor, thrown by other • Other individually adjusted relevant sport-specific activities
10	• Unilateral stance • 2 sets medial/lateral direction • 2 sets diagonal direction • Ball against wall/floor, thrown by other • Other individually adjusted relevant sport-specific activities	• 2 sets with injured limb on roller board, anterior/posterior plus medial/lateral plus rotation • 2 sets with uninvolved limb on roller board, anterior/posterior plus medial/lateral plus rotation • Ball against wall/floor, thrown by other • Other individually adjusted relevant sport-specific activities	• Unilateral stance • 2 sets anterior/posterior plus medial/lateral plus rotation • Ball against wall/floor, thrown by other • Other individually adjusted relevant sport-specific activities

[a]From Eitzen et al. [4] with permission from the Journal of Orthopaedic and Sports Physical Therapy

Table 9.2 Soreness rules for monitoring and educating patients on progression of rehabilitation[a]

Criterion	Action
Soreness during warm-up that continues	2 days off, drop down one level
Soreness during warm-up that goes away	Stay at level that led to soreness
Soreness during warm-up that goes away but redevelops during session	2 days off, drop down one level
Soreness the day after lifting (not muscle soreness)	1 day off, do not advance program to the next level
No soreness	Advance one level/week, or as instructed by healthcare professional

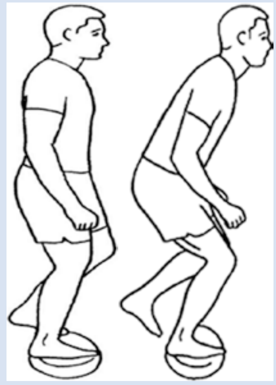
[a]From Fees et al. [20] with permission from Sage Publications

(NMES) [37, 38]. During the middle postoperative stage, it is critical to determine the optimal load for the patient depending on their response to treatment, graft type, and healing times. Exercise and activity progression should ensure that the patient is adequately challenged [37]. As the patient transitions to the late phases of rehabilitation, the involved quadriceps muscle strength should be at least 80% of the uninvolved, tested using a maximal volitional isometric contraction (MVIC). High-intensity NMES is no longer needed once a patient demonstrates a QI of 80%. When patients demonstrates full ROM, ≥80% quadriceps index, trace or less effusion [7], and minimal to no joint pain or soreness (clinical impairment resolution), they may begin a running progression when they are at least 12 weeks or more after ACLR. The late phase of postoperative rehabilitation is focused on continuing activity progression, quadriceps strength, and beginning to focus on sport-specific training. The patient needs to maintain adequate quadriceps strength, have confidence in RTS, and demonstrate no other deficits prior to being considered for standardized testing for RTS.

Table 9.3

Exercise	Description	Sets by number of repetitions	Figures
Stationary cycle	Continuous warm-up at your preferred resistance	10 min	
Treadmill	Continuous warm-up at your preferred speed	10 min	
Elliptical trainer	Continuous warm-up at your preferred resistance	10 min	

Table 9.3 (continued)

Exercise	Description	Sets by number of repetitions	Figures
Single-limb squat	Maintain knee-over-toe position	3 × 8	
Step-up	Maintain knee-over-toe position	2 × 10	
Squat on BOSU	Maintain knee alignment and core stability. Squat quickly down and up	2 × 20	

(continued)

Table 9.3 (continued)

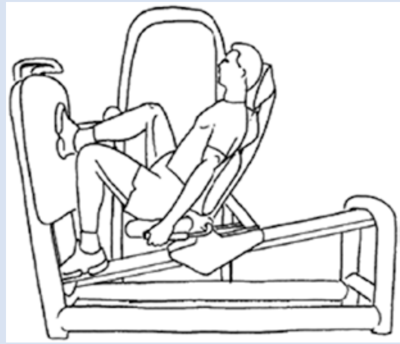
Exercise	Description	Sets by number of repetitions	Figures
Single-limb leg press	Start in 90° knee flexion	3 × 6 (+2)	 
Single-limb knee extension	Start in 90° knee flexion	4 × 6 (+2)	 

Table 9.3 (continued)

Exercise	Description	Sets by number of repetitions	Figures
Squats	Squat slowly down to 90° knee flexion, stop, lift quickly up again	3 × 8 (+2)	
Leg curl	Lift quickly up, stop, and then slowly down to full extension	3 × 8 (+2)	 

(continued)

Table 9.3 (continued)

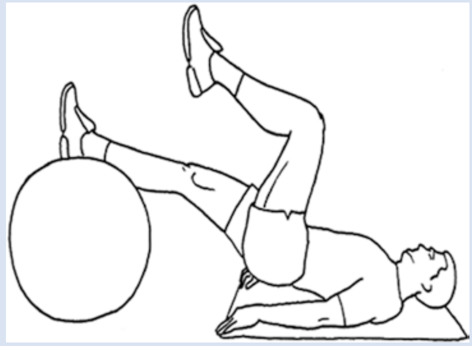
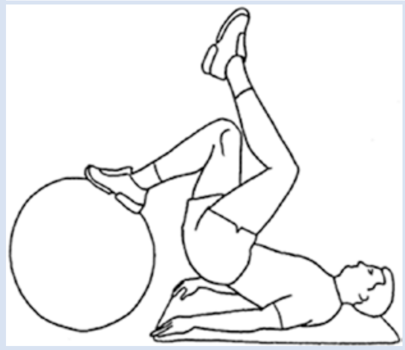
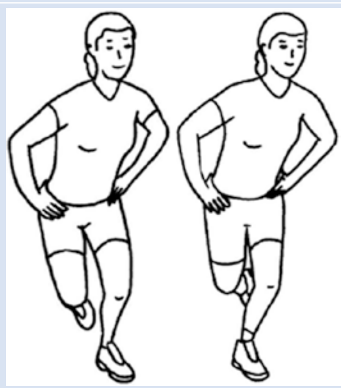
Exercise	Description	Sets by number of repetitions	Figures
Hamstring on Fitball	One foot on top of the ball, lift back and pelvis up, pull ball toward you	3 × 6	 
Single-leg hop	Hop up on step, stop, continue down and directly 1 hop forward with a soft controlled landing	1 × 15	  

Table 9.3 (continued)

Exercise	Description	Sets by number of repetitions	Figures
Sideways single-leg hop	Start on 1 side of a board. Hop quickly sideways and stop after 3 hops. Continue and stop 5 times	3 × 15	 
Skating	Start on 1 leg, hop sideways, perform a soft, deep, and steady landing on 1 leg, hop back to the other side	2 × 20	

All exercises are to be performed at each training session. Two to three series in each session. Training sessions minimum two, maximum four times a week. Progression from increasing loads on the strength exercises and for higher steps, longer/higher jumps, movement in several directions and more wobbly surfaces for the neuromuscular and plyometric exercises

Table reprinted from Eitzen I, Moksnes H, Snyder-Mackler L, Risberg MA. A progressive 5-week exercise therapy program leads to significant improvement in knee function early after anterior cruciate ligament injury. *J Orthop Sports Phys Ther*. 2010;40:705-721. https://doi.org/10.2519/jospt.2010.3345 ©*Journal of Orthopaedic and Sports Physical Therapy*®. Illustrations ©2018 ExorLive.com®

9.5 Return to Sport Timeline and Criteria

We use a battery of functional performance tests and patient-reported outcomes that to guide clinical decision making. We use four single-leg hop tests [39] including a single hop for distance (Fig. 9.3), crossover hop for distance (Fig. 9.4), triple hop for distance, and a 6-m timed hop, performed in this order. The uninvolved limb is tested first, then the involved limb. Hop test performance is compared between legs using a LSI as:

$$\text{LSI Calculation for 3 Single-Limb Hops for Distance}^{*}$$
$$(\text{Involved Limb Distance} \div \text{Uninvolved Limb Distance}) \times 100\%$$
$$\text{LSI Calculation for 6 Meter Timed Hop}$$
$$(\text{Uninvolved Limb Time} \div \text{Involved Limb Time}) \times 100\%$$
$$*\text{6 meter timed hop is reversed}$$

Patients must achieve ≥90% LSI on all hop tests in order to meet our RTS criteria and be cleared by their health care provider.

Quadriceps index (QI) is used to assess strength. The index is calculated as:

$$\text{Quadriceps Index}$$
$$(\text{Involved Limb MVIC} \div \text{Uninvolved Limb MVIC}) \times 100\%$$

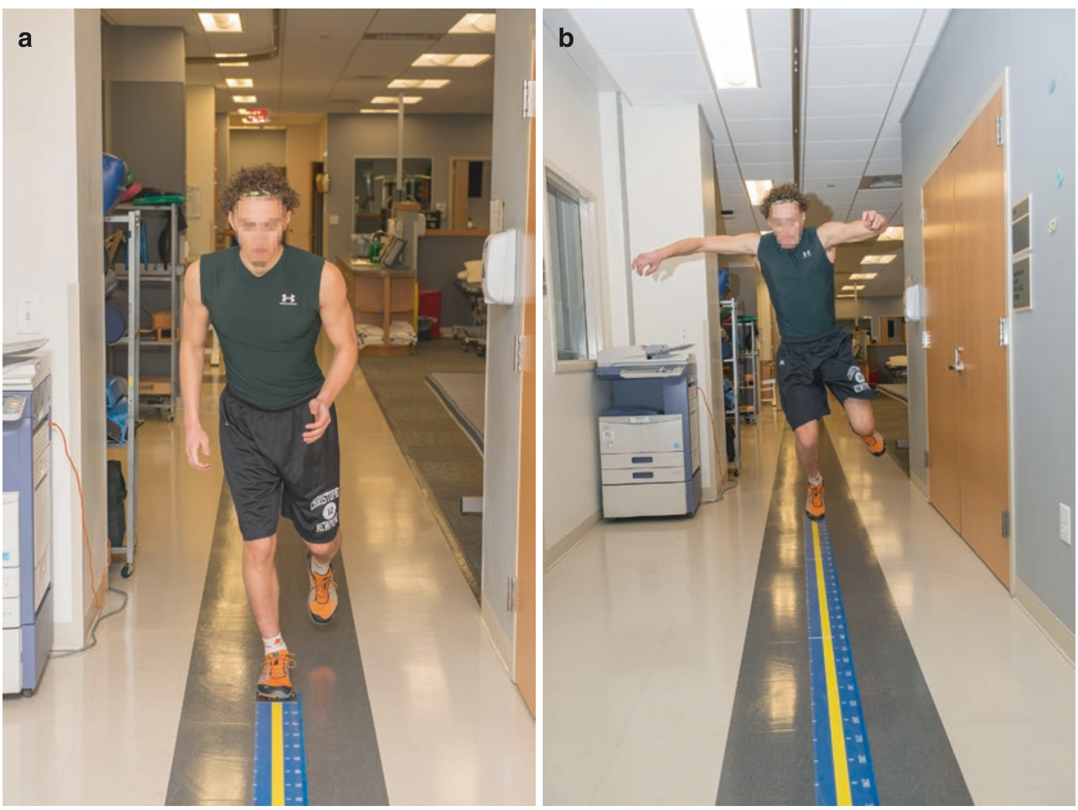


Fig 9.3 (**a**, **b**) Single hop for distance

Fig 9.4 Crossover hop for distance

Fig 9.5 Quadriceps strength testing on an isokinetic dynamometer

Quadriceps strength should be tested with an MVIC using isometric or isokinetic dynamometry whenever possible [40] (Fig. 9.5). One-repetition maximum (1-RM) on a knee extension machine (leg extension) is the best alternative for clinical decision making [40]. Drawbacks to using hand-held dynamometry include difficulty with stabilization and proper directional force application. Clinicians should avoid assessing a 1-RM leg press whenever possible due to the inability to isolate the quadriceps resulting in an overestimation of quadriceps strength [40]. It is best to test the uninvolved limb prior to the involved limb with any of these methods. A score of ≥90% QI is required to meet the strength component of the RTS criteria.

We recommend monitoring effusion throughout the rehabilitation process using the stroke test (Table 9.4), which is reliable when used for grading intra-capsular swelling (i.e., effusion) in the knee [7]. An increase in effusion after progression of activity may indicate that there is unresolved pathology and/or the level at which the patient is performing may be overloading the joint [20, 21]. We apply joint-specific soreness rules that initially were written for the upper extremity [20] but have been applied to lower extremity injuries such as after ACL injury and

Table 9.4 The stroke test [7]

Effusion grading scale of the knee joint based on the stroke test	
Grade	Test result
Zero	No wave produced on downstroke
Trace	Small wave on medial side with downstroke
1+	Larger bulge on medial side with downstroke
2+	Effusion spontaneously returns to medial side after upstroke (no downstroke necessary)
3+	So much fluid that it is not possible to move the effusion out of the medial aspect of the knee

From Adams et al. [21] with permission from the Journal of Orthopaedic and Sports Physical Therapy

ACLR to progress the patient in postoperative rehabilitation and into the RTS phase [21]. Safe exercise progression is an important concept we include in our patient education when teaching home exercise programs and self-progression.

Finally, we use patient-reported outcome measures including the Knee Outcome Survey Activities of Daily Living Subscale [41] (KOS-ADLS), aforementioned IKDC 2000, and the Global Rating Score of Perceived Function (GRS) [42]. The KOS-ADLS, a reliable, valid, and responsive outcome measure, assesses knee function during activities of daily living [41]. A higher number represents less limitation in knee function in daily life, with a score of 100% equating to no limitation. To rate overall knee function compared to knee function prior to injury and surgery, we use the GRS, which is a single item rating from 0 to 100%. Here, a high percentage indicates higher perceived functional recovery. To meet our RTS criteria, patients must score ≥90% on the KOS-ADLS and GRS.

Although patients pass our RTS criteria, we withhold immediate unrestricted RTS and continue with a progression into full, unopposed participation in sports. Our progression includes task-specific drills that mimic the demands of the athlete's sport, beginning with individual drill and progressing into unopposed team play, then opposed individual play, and finally opposed team play. After this, we recommend the athlete begins full participation in practice and scrimmages, and then return to competition. We recommend that full, unrestricted return to level I and II sports [43, 44] is delayed until at least 9 months [45]. The DOC data show that athlete's reinjury rate is reduced by 51% for each month RTS is delayed until 9 months with additional evidence that similar risk reduction persists until 12 months [26]. Athletes who passed all of our RTS criteria and returned after 9 months were 84% less likely to reinjure their knee within 24 months after ACLR [26]. This decrease in knee reinjury rate further supports the use of time-based and functional RTS criteria. The 2-year rate of knee reinjury in patients who returned to level I sport after surgery was 30%, compared to 8% for those who returned to lower level sports, highlighting the importance of educating patients returning to level I sports of their increased risk of reinjury. Additionally, those who do not meet criteria for RTS, and demonstrate lingering quadriceps strength asymmetry, may have up to a four times greater risk of rupturing their ACL graft [27]. Returning to a level I sport prior to 9 months postoperatively, and not achieving 90% QI prior to RTS were independent risk factors for reinjury of the ACL [26]. Recent evidence in a separate cohort of young, high-level athletes corroborates the need to delay RTS for preventing second injury, even among those who meet our RTS criteria and have no lingering impairments [24].

9.6 Outcomes After Extended Preoperative Rehabilitation

While preoperative knee function has been associated with outcomes after ACL injury and reconstruction, few have looked at long-term outcomes of patients who have undergone extensive, progressive preoperative and postoperative rehabilitation. We compared the postoperative patient-reported outcomes from the Norwegian Arm (NAR) of the DOC to the outcomes from the Norwegian National Knee Ligament Registry (NKLR) [3]. The NAR group underwent a 5-week rehabilitation program [4], with the recommendation that the patients achieve ≥90% QI and ≥90% inter-limb symmetry with hop testing prior to ACLR. The patients in the NAR group completed the KOOS, a previously validated [46] knee-specific self-assessment, after the completion of extended preoperative rehabilitation and again at 2 years postoperatively. A score difference of 10 points in any of the subsets was considered a clinically meaningful difference [47]. The NAR group had significantly higher scores in all subscales of the KOOS preoperatively after the completion of the 5-week rehabilitation program compared to those in the NKLR. Higher patient-reported outcomes in the NAR group continued at 2 years, in addition to clinically relevant differences found in the KOOS Symptoms, Sports, and Quality of Life subscales. The normative range values of the KOOS subscales for the NAR cohort ranged from 86% to 94%, meaning these ACLR patients had outcomes comparable to the general population, while the NKLR had 51–76% normative range values.

A similar comparison of the US arm of the DOC to a large registry in the USA, the Multicenter Orthopedic Outcomes Network (MOON), looked at the effects of preoperative rehabilitation on outcomes after ACLR [1, 2]. Specifically, the study looked at the IKDC subjective knee form scores, KOOS results, and overall RTS rates 2 years after ACLR. The patients in the DOC group were given the 5-week progressive preoperative rehabilitation [4] described in the aforementioned NAR group. The DOC group, compared to the MOON cohort, had significantly higher IKDC scores after preoperative rehabilitation, and also at 2 years after ACLR. DOC patients also had clinically meaningfully higher KOOS scores at 2 years after ACLR. RTS rates in the DOC group were 72%, significantly higher than the 63% in the MOON cohort group. The 72% rate for return to preinjury sport level also compares favorably to the 65% rate published in a meta-analysis by Ardern et al. [48]. The consistent, positive results seen in the DOC reinforce the added benefit of extended preoperative rehabilitation beyond clinical impairment resolution. These results carry over not only through the immediate postoperative phase but also continue to be meaningful at 2 years after ACLR.

9.7 Summary

ACLR patients from the DOC who followed the extended preoperative rehabilitation program, beyond clinical impairment resolution, and a criterion-based postoperative rehabilitation program showed superior outcomes 2 years postoperatively to outcomes from similarly matched cohorts who underwent standardized care. Patients who are initially classified as noncopers may benefit from the use of extended preoperative rehabilitation to improve their function and outcomes. The overall aim of the progressive preoperative rehabilitation program is to maximize pre and therefore postoperative rehabilitation functional outcomes.

Impairment resolution is critical prior to surgery but it is not enough. Health care providers should add a rigorous preoperative rehabilitation that includes neuromuscular, strength, and plyometric and agility training to maximize functional and RTS outcomes.

9.8 Critical Points

- Extended preoperative rehabilitation plus criterion-based postoperative rehabilitation, compared to postoperative rehabilitation alone, lead to higher patient-reported outcomes, functional outcomes, and RTS rates.
- Athletes should achieve preoperative milestones (little to no effusion and pain, full knee ROM, no obvious gait impairments) and have strong quadriceps strength preoperatively, as higher preoperative values lead to higher postoperative values.
- Objective postoperative RTS criteria (≥90% QI, ≥90% hop tests, ≥90% KOS-ADLS, ≥90% GRS) including delayed RTS time frames (9–12 months for pivoting sports) are essential for successful RTS and reducing reinjury rates.
- Health care providers should consider extended preoperative rehabilitation including progressive strengthening and perturbation training as a strategy to improve outcomes after ACLR.

References

1. Failla MJ, Logerstedt DS, Grindem H, Axe MJ, Risberg MA, Engebretsen L, et al. Does extended preoperative rehabilitation influence outcomes 2 years after ACL reconstruction? A comparative effectiveness study between the MOON and Delaware-Oslo ACL cohorts. Am J Sports Med. 2016;44(10):2608–14.
2. Failla MJ, Logerstedt D, Grindem H. Corrigendum. Am J Sports Med. 2017;45(5):NP9. Available from: http://journals.sagepub.com/doi/10.1177/0363546517696318.
3. Grindem H, Granan LP, Risberg MA, Engebretsen L, Snyder-Mackler L, Eitzen I. How does a combined

preoperative and postoperative rehabilitation programme influence the outcome of ACL reconstruction 2 years after surgery? A comparison between patients in the Delaware-Oslo ACL cohort and the Norwegian National Knee Ligament Registry. Br J Sports Med. 2015;49(6):385–9.
4. Eitzen I, Moksnes H, Snyder-Mackler L, Risberg MA. A progressive 5-week exercise therapy program leads to significant improvement in knee function early after anterior cruciate ligament injury. J Orthop Sport Phys Ther. 2010;40(11):705–21. Available from: http://www.jospt.org/doi/10.2519/jospt.2010.3345
5. Fitzgerald GK, Axe MJ, Snyder-Mackler L, et al. Knee Surg Sports Traumatol Arthrosc. 2000;8(2):76–82. Available from: http://www.molbiolcell.org/cgi/doi/10.1091/mbc.E02-08-0511
6. Hägglund M, Waldén M, Thomeé R. Should patients reach certain knee function benchmarks before anterior cruciate ligament reconstruction? Does intense "prehabilitation" before anterior cruciate ligament reconstruction influence outcome and return to sports? Br J Sports Med. 2015;49(22):1423–4.
7. Sturgill LP, Snyder-Mackler L, Manal TJ, Axe MJ. Interrater reliability of a clinical scale to assess knee joint effusion. J Orthop Sport Phys Ther. 2009;39(12):845–9. Available from: http://www.jospt.org/doi/10.2519/jospt.2009.3143
8. Chmielewski TL, Hurd WJ, Rudolph KS, Axe MJ, Snyder-Mackler L. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. Phys Ther. 2005;85(8):740–54.
9. Logerstedt D, Lynch A, Axe MJ, Snyder-Mackler L. Pre-operative quadriceps strength predicts IKDC2000 scores 6 months after anterior cruciate ligament reconstruction. Knee. 2013;20(3):208–12. https://doi.org/10.1016/j.knee.2012.07.011.
10. Eitzen I, Holm I, Risberg MA. Preoperative quadriceps strength is a significant predictor of knee function two years after anterior cruciate ligament reconstruction. Br J Sports Med. 2009;43(5):371–6.
11. Thoma LM, Grindem H, Logerstedt D, Axe M, Engebretsen L, Risberg MA, et al. Coper classification early after ACL rupture changes with progressive neuromuscular and strength training and is associated with two-year success: the Delaware-Oslo ACL Cohort Study. Am J Sports Med. 2019;47:807.
12. Arundale AJH, Bizzini M, Giordano A, Hewett TE, Logerstedt DS, Mandelbaum B, et al. Exercise-based knee and anterior cruciate ligament injury prevention. J Orthop Sport Phys Ther. 2018;48(9):A1–42.. Available from: https://www.jospt.org/doi/10.2519/jospt.2018.0303
13. Hartigan E, Axe MJ, Snyder-Mackler L. Perturbation training prior to ACL reconstruction improves gait asymmetries in non-copers. J Orthop Res. 2009;27(6):724–9.
14. Hurd WJ, Chmielewski TL, Snyder-Mackler L. Perturbation-enhanced neuromuscular training alters muscle activity in female athletes. Knee Surg Sports Traumatol Arthrosc. 2006;14(1):60–9.
15. Fitzgerald GK, Axe MJ, Snyder-Mackler L. The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physically active individuals. Phys Ther. 2000;80(2):128. Available from: https://academic.oup.com/ptj/article/80/2/128/2842479/The-Efficacy-of-Perturbation-Training-in
16. Morrissey MC, Perry MC, King JB. Is knee laxity change after ACL injury and surgery related to open kinetic chain knee extensor training load? Am J Phys Med Rehabil. 2009;88(5):369–75.
17. Perry MC, Morrissey MC, Morrissey D, Knight PR, McAuliffe TB, King JB. Knee extensors kinetic chain training in anterior cruciate ligament deficiency. Knee Surg Sports Traumatol Arthrosc. 2005;13(8):638–48. https://doi.org/10.1007/s00167-004-0603-8.
18. Tagesson S, Öberg B, Good L, Kvist J. A comprehensive rehabilitation program with quadriceps strengthening in closed versus open kinetic chain exercise in patients with anterior cruciate ligament deficiency: a randomized clinical trial evaluating dynamic tibial translation and muscle function. Am J Sports Med. 2008;36(2):298–307.
19. Mikkelsen C, Werner S, Eriksson E. Closed kinetic chain alone compared to combined open and closed kinetic chain exercises for quadriceps strengthening after anterior cruciate ligament reconstruction with respect to return to sports: a prospective matched follow-up study. Knee Surg Sports Traumatol Arthrosc. 2000;8(6):337–42. https://doi.org/10.1007/s001670000143.
20. Fees M, Decker T, Snyder-mackler L, Axe MJ. Upper extremity weight-training modifications for the injured athlete: a clinical perspective. Am J Sports Med. 1998;26(5):732–42.
21. Adams D, Logerstedt D, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. J Orthop Sport Phys Ther. 2012;42(7):601–14. Available from: http://www.jospt.org/doi/10.2519/jospt.2012.3871
22. Palmieri-Smith RM, Thomas AC. A neuromuscular mechanism of posttraumatic osteoarthritis associated with ACL injury. Exerc Sport Sci Rev. 2009;37(3):147–53.
23. Logerstedt D, Grindem H, Lynch A, Eitzen I, Engebretsen L, Risberg MA, et al. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo ACL cohort study. Am J Sports Med. 2012;40(10):2348–56.
24. Capin JJ, Khandha A, Zarzycki R, Manal K, Buchanan TS, Snyder-Mackler L. Gait mechanics and second ACL rupture: implications for delaying return-to-sport. J Orthop Res. 2017;35(9):1894–901.
25. Nawasreh Z, Logerstedt D, Cummer K, Axe MJ, Risberg MA, Snyder-Mackler L. Do patients failing return-to-activity criteria at 6 months after anterior cruciate ligament reconstruction continue demonstrating deficits at 2 years? Am J Sports Med. 2017;45(5):1037–48.

26. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med. 2016;50(13):804–8.
27. Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. Br J Sports Med. 2016;50(15):946–51.
28. Yoo JH, Lim BO, Ha M, Lee SW, Oh SJ, Lee YS, et al. A meta-analysis of the effect of neuromuscular training on the prevention of the anterior cruciate ligament injury in female athletes. Knee Surg Sports Traumatol Arthrosc. 2010;18(6):824–30.
29. Sugimoto D, Myer GD, Foss KDB, Hewett TE. Specific exercise effects of preventive neuromuscular training intervention on anterior cruciate ligament injury risk reduction in young females: meta-analysis and subgroup analysis. Br J Sports Med. 2015;49(5):282–9.
30. Stevenson JH, Beattie CS, Schwartz JB, Busconi BD. Assessing the effectiveness of neuromuscular training programs in reducing the incidence of anterior cruciate ligament injuries in female athletes: a systematic review. Am J Sports Med. 2015;43(2):482–90.
31. Risberg MA, Grindem H, Øiestad BE. We need to implement current evidence in early rehabilitation programs to improve long-term outcome after anterior cruciate ligament injury. J Orthop Sport Phys Ther. 2016;46(9):710–3. https://doi.org/10.2519/jospt.2016.0608.
32. Manal TJO, Snyder-mackler L. Practice guidelines for anterior cruciate ligament rehabilitation: a criterion-based rehabilitation progression. Oper Tech Orthop. 1996;6(3):190–6.
33. Wright RW, Haas AK, Anderson J, Calabrese G, Cavanaugh J, Hewett TE, et al. Anterior cruciate ligament reconstruction rehabilitation: MOON guidelines. Sports Health. 2015;7(3):239–43.
34. Logerstedt DS, Snyder-Mackler L, Ritter RC, Axe MJ, Godges JJ. Knee stability and movement coordination impairments: knee ligament sprain. J Orthop Sport Phys Ther. 2010;40(4):A1–37. Available from: http://www.jospt.org/doi/10.2519/jospt.2010.0303
35. Logertedt FS, Scalzitti D, Arna M, Engebretsen L, Webster K, Feller J, Snyder-Mackler L, Axe MJ, McDonough CM. Knee stability and movement coordination impairments: knee ligaments sprain revision 2017. J Orthop Sports Phys Ther. 2017;47(11):1–47. Available from: https://sci-hub.hk/10.2519/jospt.2017.0303
36. Capin JJ, Behrns W, Thatcher K, Arundale A, Smith AH, Snyder-Mackler L. On-ice return-to-hockey progression after anterior cruciate ligament reconstruction. J Orthop Sport Phys Ther. 2017;47(5):324–33. Available from: http://www.jospt.org/doi/10.2519/jospt.2017.7245
37. Snyder-Mackler L, Delitto A, Stralka SW, Bailey SL. Use of electrical stimulation to enhance recovery of quadriceps femoris muscle force production in patients following anterior cruciate ligament reconstruction. Phys Ther. 1994;74(10):901–7. Available from: https://academic.oup.com/ptj/article/2729152/Use
38. Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. J Bone Joint Surg Am. 1995;77(8):1166–73.
39. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med. 1991;19(5):513–8.
40. Sinacore JA, Evans AM, Lynch BN, Joreitz RE, Irrgang JJ, Lynch AD. Diagnostic accuracy of handheld dynamometry and 1-repetition-maximum tests for identifying meaningful quadriceps strength asymmetries. J Orthop Sports Phys Ther. 2017;47(2):97–107. Available from: http://www.jospt.org/doi/10.2519/jospt.2017.6651
41. Irrgang JJ, Snyder-Mackler L, Wainner RS, Fu FH, Harner CD. Development of a patient-reported measure of function of the knee. J Bone Joint Surg Am. 1998;80(8):1132–45. Available from: http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=9730122
42. Gardinier ES, Manal K, Buchanan TS, Snyder-Mackler L. Clinically-relevant measures associated with altered contact forces in patients with anterior cruciate ligament deficiency. Clin Biomech. 2014;29(5):531–6. https://doi.org/10.1016/j.clinbiomech.2014.03.011.
43. Hefti E, Müller W, Jakob RP, Stäubli HU. Evaluation of knee ligament injuries with the IKDC form. Knee Surg Sports Traumatol Arthrosc. 1993;1(3–4):226–34.
44. Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR. Fate of the ACL-injured patient. A prospective outcome study. Am J Sports Med. 1993;22(5):632–44. Available from: http://www.ncbi.nlm.nih.gov/pubmed/7810787
45. Nagelli CV, Hewett TE. Should return to sport be delayed until 2 years after anterior cruciate ligament reconstruction? Biological and functional considerations. Sports Med. 2017;47(2):221–32.
46. Roos EM, Roos HP, Lohmander LS, Ekdahl C, Beynnon BD. Knee Injury and Osteoarthritis Outcome Score (KOOS)—development of a self-administered outcome measure. J Orthop Sport Phys Ther. 1998;28(2):88–96. Available from: http://www.jospt.org/doi/10.2519/jospt.1998.28.2.88
47. Roos EM, Lohmander L. The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis. Health Qual Life Outcomes. 2003;1:64.
48. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med. 2014;48(21):1543–52.

10 Intraoperative Considerations Crucial for a Successful Outcome

Frank R. Noyes and Sue Barber-Westin

10.1 Introduction

This chapter discusses the indications and contraindications for anterior cruciate ligament (ACL) reconstruction, graft options, preoperative planning, anatomic graft placement issues, and treatment of additional injuries that may occur to the menisci and other knee ligaments. Acute complete ACL ruptures are treated first with rehabilitation until pain and swelling subside and joint motion and muscle function are restored (see Chap. 8). Reconstruction is then performed if the appropriate indications are met. However, even with surgery, patients are informed that an ACL rupture is a serious injury, and it is unlikely that they will ever have a truly normal knee joint. The injury may also involve a bone bruise and chondral damage, with sequelae for future joint symptoms. The treatment of partial ACL ruptures has been discussed elsewhere [1].

Upon the initial patient presentation, a comprehensive physical examination requires assessment of knee flexion and extension, patellofemoral indices, tibiofemoral crepitus, tibiofemoral joint line pain, muscle strength, and gait abnormalities. The medial posterior tibiofemoral step-off on the posterior drawer test is done at 90° of flexion. The integrity of the ACL is determined with KT-2000 arthrometer testing (134 N force) and the pivot shift test that is recorded on a scale of 0 to III, with a grade of 0 indicating no pivot shift; grade I, a slip or glide; grade II, a jerk with gross subluxation or clunk; and grade III, gross subluxation with impingement of the posterior aspect of the lateral side of the tibial plateau against the femoral condyle. Radiographs include standing anteroposterior (AP) at 0°, lateral at 30° of knee flexion, weight-bearing posteroanterior (PA) at 45° of knee flexion, and patellofemoral axial views. Double-stance full-standing radiographs of both lower extremities are obtained in knees in which varus or valgus lower extremity alignment is detected on clinical examination. Magnetic resonance imaging (MRI) is performed to provide further details of the condition of the articular cartilage and menisci and includes fast-spin-echo techniques and 3-Telsa articular cartilage T-2 mapping when necessary to obtain superior-quality articular cartilage images [2, 3].

10.1.1 Indications for ACL Reconstruction

Patients who are highly motivated to return to sport (RTS) or who are involved with strenuous occupations are considered for reconstruction [4]. In patients with a concomitant displaced bucket-

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_10

handle meniscus tear, surgery within 7–10 days is required to reduce the meniscus to a normal location and repair the tear. The ACL reconstruction may be performed at the same setting; however, knees with excessive swelling and pain undergo a staged meniscus repair first. After an appropriate period of rehabilitation, ACL reconstruction is then performed.

Repairable meniscus tears almost always indicate a concurrent ACL reconstruction. Otherwise, the success of the meniscus repair may be compromised [5–7]. A grade III pivot shift and grossly positive Lachman (increased ≥10-mm anterior tibial translation) indicate involvement of the secondary ligamentous restraints and, in our experience, an increased risk of giving-way reinjuries with recreational activities, and reconstruction is frequently recommended.

Systematic reviews have demonstrated that ACL reconstruction reduces the incidence of subsequent meniscus injuries, reduces the need for further operations, and results in greater improvements in activity levels [8]. In patients who undergo reconstruction and in whom the menisci are retained, there is a lower incidence of knee osteoarthritis [9, 10]. Mather and associates [11] reported that, in the short term, ACL reconstruction was less costly (cost reduction of $4503) and more effective compared with rehabilitation. In the long term, the mean lifetime cost to society for a patient undergoing ACL reconstruction was calculated to be $38,121 compared with $88,538 for nonoperative treatment with rehabilitation.

10.1.2 Contraindications for ACL Reconstruction

Patients involved in low-impact activities or who are willing to avoid strenuous athletic and occupational activities that place the knee at increased risk for reinjury may not require ACL reconstruction. These patients undergo rehabilitation to regain muscle strength and neuromuscular function and are counseled on the risk of future giving-way reinjuries and potential damage to the joint. Patients who are unable to participate or be compliant with postoperative rehabilitation are not surgical candidates.

The presence of symptomatic patellofemoral or tibiofemoral arthritis is a general contraindication to ACL surgery, because pain symptoms remain postoperatively. Weight-bearing 45° PA views determine the millimeters of remaining medial or lateral tibiofemoral joint space. In knees with absent or nearly absent joint space, conservative measures are instituted until such time that partial or total joint replacement is warranted.

Patients with symptomatic medial tibiofemoral arthritis and varus malalignment require high tibial osteotomy. These patients often do not require subsequent ACL surgery due to limitations in activities from the joint damage. Patients with lower extremity muscle atrophy require rehabilitation until adequate muscle function has been restored. These patients have an increased risk for postoperative complications including quadriceps muscle shutdown, patella infera, and arthrofibrosis. Complex regional pain syndrome is a contraindication to surgery.

Patients with a body mass index of 30 or greater are usually not surgical candidates. A history of prior infection with subsequent joint arthritis often contraindicates ACL surgery. There may be associated medical conditions contraindicating surgery. The use of nicotine products is strongly discouraged and absolutely contraindicated if osteotomy alignment procedures are required.

10.1.3 Preoperative Planning

All abnormalities or potential problems are addressed preoperatively, including patient expectation issues, muscular weakness, painful neuromas, residual pain syndromes, and anterior knee pain due to patellofemoral cartilage damage. Considerable counseling and patient education are required on the expected results and outcomes from the reconstruction. This is especially important in knees with preexisting arthritis or loss of meniscal function or those that require additional major operative procedures. A surgeon-rehabilitation team is required to provide instruction on rehabilitation to ensure that the postoperative exercise program will be successfully followed by the patient. The patient and family consult with the physical therapy team before surgery to ensure that the postoperative rehabilitation requirements are thoroughly understood. Disclosure is required that approximately 50% of patients in whom a bone-patellar tendon-bone (B-PT-B) autograft is used will have a small area of numbness just lateral to the patellar tendon.

Knees with grossly positive clinical laxity tests have involvement of the secondary ligament restraints, primarily the lateral structures. Associated medial or lateral ligament laxity is an indication for medial or lateral ligament reconstruction. A summary of the essential aspects of ACL reconstruction is shown in Table 10.1.

It is important to determine the ACL graft length well before surgery to ensure a mismatch does not occur between intra-articular length of the tunnels and the length of the graft. The length of the patellar tendon is determined on lateral radiographs. The normal patellar length based on the Linclau technique [13] is a 1:1 ratio with the patellar tendon in the 35-mm range. The intra-articular ACL length is measured on the lateral MRI, and this length is matched with the graft.

10.1.4 ACL Graft Selection

The two most common autograft tissue sources for ACL reconstruction are B-PT-B and semitendinosus-gracilis (STG) tendons. A quadriceps tendon-patellar bone (QT-PB) autograft is also an excellent graft to substitute for STG tendons in small females and in other situations such as ACL revision reconstructions. We prefer B-PT-B autogenous grafts over allografts in athletes, a recommendation supported by multiple long-term studies [14–18]. In addition, several investigations have documented a higher rate of ACL reconstruction failure in allografts compared with autografts, especially in younger active patients [15, 19–26]. Although allografts offer technical ease and reduced donor site pain, there are additional risks of disease transmission, a biomechanically inferior graft, and biological reaction to irradiation and chemical sterilization processing [27].

A B-PT-B autograft is not recommended if there is associated patellofemoral arthritis, anterior knee pain, or history of patellar subluxation or dislocation. A B-PT-B autograft is not performed when patient issues suggest a decreased ability to manage the initial postoperative graft harvest-related pain. In recreational athletes

Table 10.1 Summary of essential aspects of ACL reconstruction

1. Autografts are recommended over allografts based on the superior healing, graft incorporation, overall higher success rates, and avoidance of transmission of disease (even though of rare incidence). Allografts are reserved for multioperated revision knees with concurrent instability where suitable graft sources are not available or special clinical cases in which a graft harvest is to be avoided
2. ACL grafts should be placed in an anatomic position within the femoral and tibial footprint. The central portion of the femoral and tibial attachment site is recommended. The native ACL femoral attachment is located entirely on the lateral wall; no fiber attachments extend to the intercondylar roof
3. The ACL graft is placed in a femoral tunnel that is located in the proximal two-thirds of the ACL footprint. A distal placement in the femoral attachment shortens the length and increases the failure rate. A tibial tunnel located in the posterior one-third of the ACL footprint results in an ineffective graft orientation. A central tibial footprint location should be achieved in the anteromedial bundle portion
4. A limited notchplasty is usually required to prevent roof impingement in extension and to have an adequate graft space between the lateral notch and the posterior cruciate ligament
5. Associated ligament injuries overload ACL grafts and require correction to prevent failure of the ACL reconstruction
6. Abnormal knee hyperextension of 12–15° may overload an ACL graft and requires operative correction. The recommended posterolateral graft reconstructive procedures for a severe hyperextension varus recurvatum deformity have been described elsewhere [12]. Certain ACL revision knees with stretching or injury to the secondary ligament restraints and a grade III pivot shift require a lateral extra-articular procedure
7. A comprehensive rehabilitation program is essential for success and return of lower extremity function. Rehabilitation principles and protocols are addressed in Chaps. 11 and 14

and more sedentary patients, a four-strand or six-strand STG autograft or QT-PB autograft is recommended. Modern soft tissue graft fixation methods have increased success rates.

10.1.4.1 Critical Points

Indications

- Complete ACL rupture
- Patient desires to return to high-risk activities (pivoting, cutting, twisting, turning)
- Acute ACL rupture and concomitant displaced bucket-handle meniscus tear

Contraindications

- Sedentary patient, no symptoms, little exposure high-risk activities
- Patient unable to participate in postoperative rehabilitation program
- Preexisting severe loss of patellofemoral or tibiofemoral compartment joint space
- Marked muscle atrophy, complex regional pain syndrome, obesity
- Prior joint infection

Preoperative planning

- Address patient expectation and goals of surgery
- Determine need for concomitant procedures, extra-articular procedures, other ligament reconstructions to correct all instabilities
- Determine ACL graft length

Graft Selection

- Prefer B-PT-B autograft in athletes, STG or QT-PB in recreational, more sedentary patients or those with patellofemoral problems.
- Allografts are rarely used and are reserved for multiligament procedures or special cases where graft harvest is to be avoided.

10.2 Intraoperative Evaluation

After the induction of anesthesia, all knee ligament subluxation tests are performed in both the injured and contralateral limbs. The amounts of increased anterior tibial translation, posterior tibial translation, lateral and medial joint opening, and external tibial rotation are documented. A thorough arthroscopic examination is conducted, noting articular cartilage surface abnormalities and the condition of the menisci. Appropriate debridement and meniscus repair (to be described) or partial excision are performed as necessary.

The lateral and medial gap tests are done during the arthroscopic examination [28]. The knee is flexed to 25–30° and a varus load of approximately 89 N applied. A calibrated nerve hook is used to measure the amount of tibiofemoral compartment opening. Knees that have 12 mm or more of joint opening at the periphery or 10 mm at the midpoint of the tibiofemoral compartment require a posterolateral or medial ligament reconstructive procedure. Studies have shown that uncorrected deficiency of other knee ligaments increases the risk of failure of ACL reconstruction [29, 30].

10.3 Graft Harvest

10.3.1 B-PT-B Autograft

A summary of the steps for the harvest of the B-PT-B autograft is shown in Table 10.2 [1]. A 3- to 4-cm vertical medial incision is made just adjacent to the medial border of the patella tendon, avoiding the tibial tubercle (Fig. 10.1). A cosmetic approach is used where the plane beneath the subcutaneous tissues is dissected to allow for a limited skin incision. The retinaculum in the middle of the patellar tendon is incised and the dissection limited only to the midportion of the patellar tendon. The retinaculum is protected to allow for closure over the bone-grafted patellar defect. A similar procedure is used at the tibial tuberosity.

The patellar tendon is incised in the midportion to 9–10 mm. The patella is displaced distally into the wound using a forked retractor placed at the superior patellar margin. A powered handheld saw with a thin-width blade is marked with a Steri-Strip 9–10 mm from the tip. A trapezoidal

Table 10.2 Summary of steps to harvest a bone-patellar tendon-bone autograft [1]

• Inflate tourniquet 275-mm pressure
• 3–4-cm incision adjacent medial border patellar tendon, medial to inferior pole of patella, mobilize skin flaps for cosmetic approach
• Retinaculum middle patellar tendon incised, limited dissection only for width of graft to be removed
• Use precut 10-mm and 22-mm paper ruler to define graft dimensions
• Patellar tendon incised in midportion
• Trapezoidal bone block graft from patella removed with fine saw cuts, osteotome, similar procedure for tibial bone block
• Sutures placed each bone block, prepared for passage
• Graft wrapped in blood-soaked sponge
• Diameter of tunnels 1 mm larger than diameter of bone block
• End of procedure, loosely approximate tendon graft harvest site with sutures
• Meticulous bone graft from core reamer patella, tibia defects. Place 2 horizontal mattress sutures inferior pole patella, superior tibial tendon attachment to hold bone grafts in defects, close anterior tissues

bone block graft from the patella is removed by angling the fine saw 15° at each side of the cut. The bone cut extends to the inferior pole, and care is taken to protect the insertion site of the patellar tendon. A 4-mm osteotome gently removes the patellar bone block. A similar procedure is followed in the harvest of the tibial bone block. The tourniquet is deflated, and a cotton sponge is placed in the wound. The graft is later wrapped in the blood-soaked sponge, which provides for protection of the graft, maintains a moist blood environment, and may allow cells to survive in the graft-remodeling process.

The bone blocks are prepared. The diameter of the tunnels will be configured 1 mm larger than the diameter of the bone block. One 2-mm drill hole is placed one-third of the way from the end of each bone block for sutures. The end sutures allow the graft to be passed into the tunnel. The bone block tip is fashioned into a bullet tip configuration for tibial tunnel passage. At the conclusion of the ACL reconstruction, closure of the patellar tendon graft harvest site is performed with loosely approximated 2-0 absorbable sutures. A coring reamer used for the tibial tunnel provides a large dowel of cancellous bone to completely fill the patella and tibia defects.

10.3.2 Graft Harvest: STG Autograft

The STG graft harvest procedure is summarized in Table 10.3. A 3- to 4-cm oblique incision is made over the pes tendons (Fig. 10.2). An anteromedial incision over a popliteal-based incision is preferred to gain maximum length of the tendons at the tibial confluent attachment. The sartorius fascia is incised directly proximal to the semitendinosus and gracilis tendons to provide an opening to protect the superficial medial collateral ligament (SMCL). Each tendon is identified, incised through the confluent distal tendon region, and then grasped at a 90° angle and rolled two to three times around a straight hemostat, which allows tension to be placed on the tendon without producing damage.

The proximal fascia about each tendon is bluntly dissected, and the semitendinosus tendon attachment to the medial gastrocnemius fascia is incised. The tendons will freely displace 10 cm. The closed-end graft harvester is passed along the trajectory of each tendon, and each tendon is transected at 20 cm for a four-strand graft or 24 cm for a six-strand graft described later.

In the four-strand graft, each tendon is looped about a 3-mm tape and the tendon end sutured to itself with a No. 2 nonabsorbable suture. A third suture (FiberLoop, Arthrex) is added at both graft tendon ends. A running 0-nonabsorbable suture is used to produce a tubed structure running from proximal to distal and then back to the proximal starting point. The graft is marked 25 mm from each end, wrapped in a blood-soaked sponge, and placed in a secure place on the back table. A six-strand graft is used in women and patients of small stature in which the STG tendon diameter is decreased and to provide added tendon substance for a 9- to 10-mm graft diameter. This avoids a 6–7-

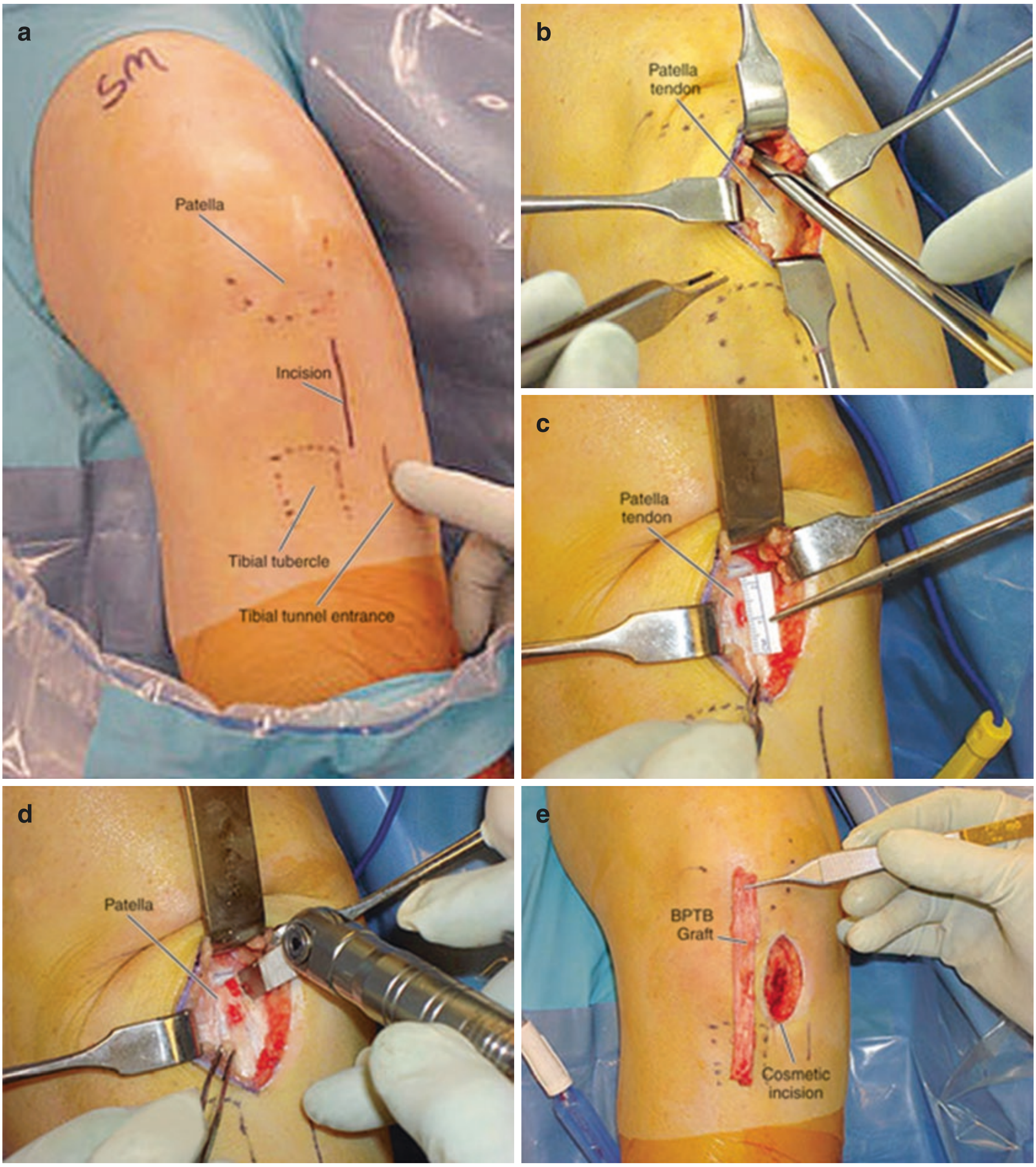


Fig. 10.1 The recommended technique for harvest of a bone-patellar tendon-bone (B-PT-B) autograft is shown. (**a**) A 3- to 4-cm skin incision, just medial to the patellar tendon, is made to avoid the bony prominence of the patella and tibial tubercle. The index finger points to the planned tibial tunnel, which can be reached through this cosmetic incision. (**b**) Mobilization of subcutaneous tissues to allow the cosmetically placed incision to be moved in a proximal-distal and medial fashion. Infrapatellar nerves when present are protected. (**c**) A ruler measures the length of the patellar tendon and a 10-mm wide patellar tendon graft is marked by two or three ink dots. (**d**) The patella is displaced distally and the patellar bone block removed. Note the saw has a tape marking a 9-mm depth to prevent from cutting too deep into the patella. The saw is angled 10–15° to produce a trapezoidal bone block. The saw carefully cuts the medial and lateral borders, making sure the bone beneath the tendon insertion has been cut to prevent a fracture of the graft. A similar technique is used for the tibial tubercle. (**e**) Appearance of the graft after harvest. (**f**) Preparation of the graft is shown. Two nonabsorbable No. 2 sutures are placed in a distal drill hole in each bone plug. The bone tendon junction is marked. The graft is wrapped in a blood-soaked sponge with the goal of maintaining viability of some tendon cells. (**g**) The skin incision is displaced distally to reach the desired position for the coronal tibial tunnel, as described in the text. (**h**) The core reamer is placed in the tibial tunnel for the graft harvest. (**i**) The bone plug removed by the core reamer (Reprinted from Noyes and Barber-Westin [1])

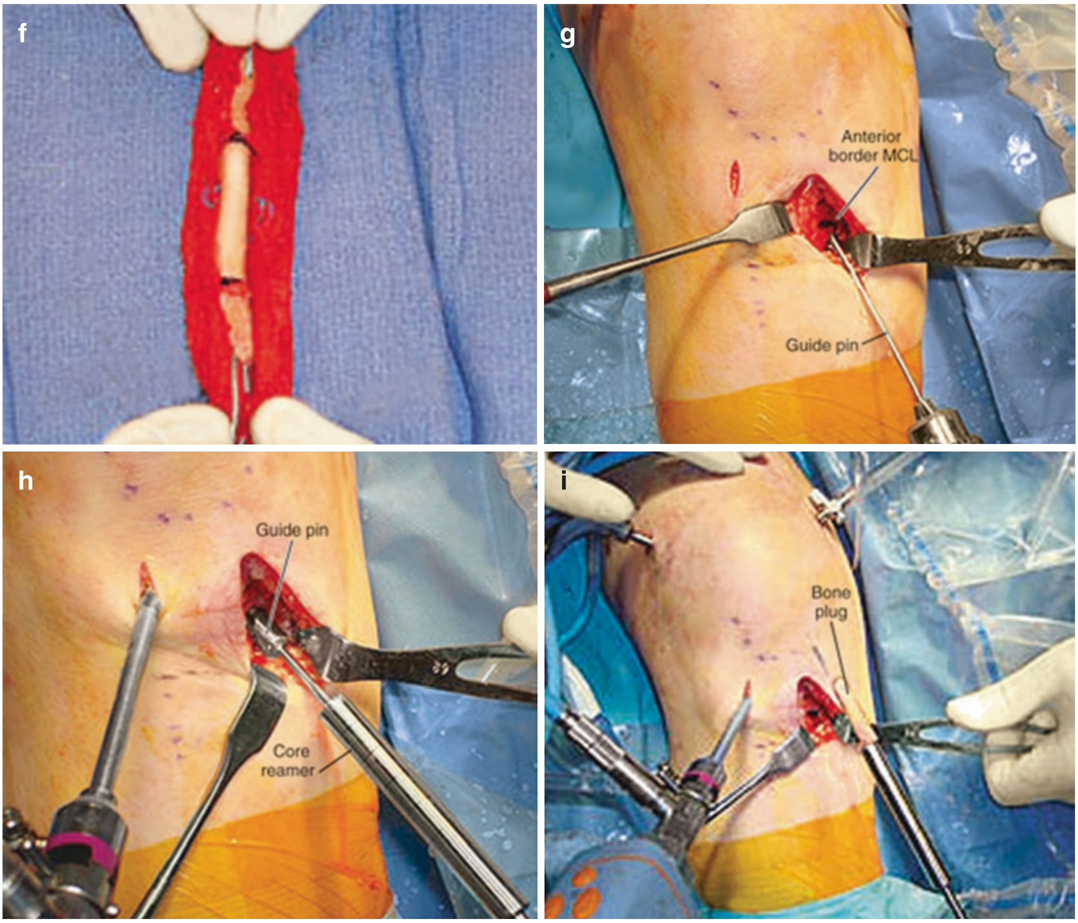


Fig. 10.1 (continued)

Table 10.3 Summary of steps to harvest a four-strand semitendinosus-gracilis autograft [1]

• 3–4-cm oblique cosmetic incision over pes tendons
• Sartorius fascia incised, provides opening to protect superficial medial collateral ligament
• Identify, palpate semitendinosus and gracilis tendons
• Turn down confluent tibial attachment
• Grasp each tendon 90° angle distal end, roll 2–3 times about straight hemostat
• Superficial tissues removed, overlying sartorius fascia protected
• Proximal fascia bluntly dissected, semitendinosus tendon attachment medial gastrocnemius fascia incised, avoid saphenous nerve
• Displace each tendon 10 cm in push-pull maneuver
• Pass graft harvester, transect each tendon 20 cm for a 4-strand graft or 24 cm for a 6-strand graft
• Prepare, wrap in blood-soaked sponge
• Six-strand graft used in women and patients of small stature

mm graft which has a known increased failure rate. The six-strand graft technique has been described in detail elsewhere [1].

10.3.3 Graft Harvest: QT-PB Autograft

A 5- to 6-cm longitudinal incision is made from the superior pole of the patella that extends proximally (Table 10.4). The prepatellar retinaculum is reflected and protected for later closure over the grafted patellar defect. The quadriceps tendon and its junction with the vastus medialis obliquus and vastus lateralis obliquus (VLO) are identified. The proximal portion of the quadriceps tendon is identified, and the graft harvest is carried 10 mm distal to the rectus femoris muscle-

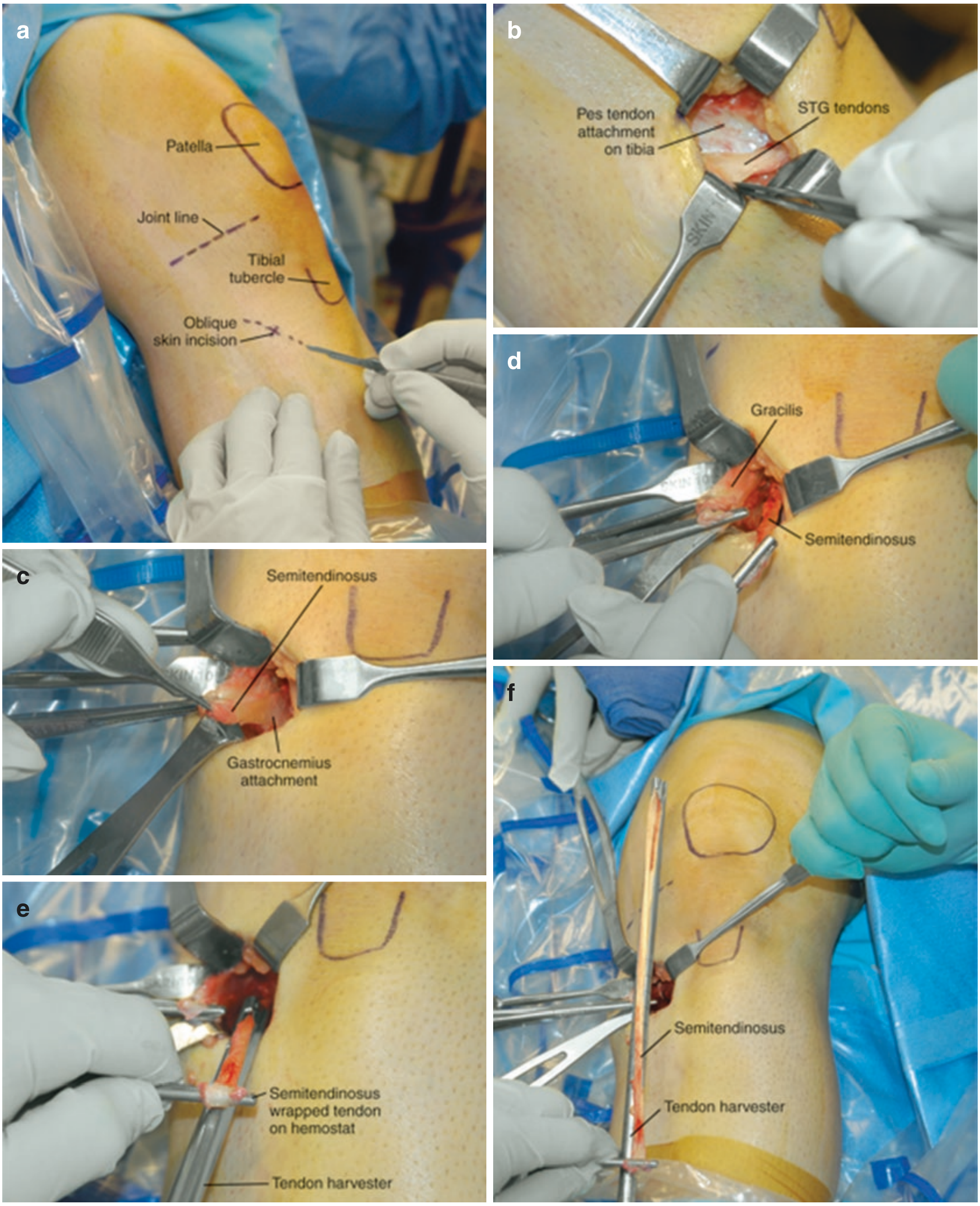


Fig. 10.2 The recommended technique for harvest of a semitendinosus-gracilis (STG) autograft is shown. (**a**) A 2-cm longitudinal or oblique incision at the AM tibia region. (**b**) An L-shaped incision at the pes tendon tibial attachment is performed, and the tendon flap is reflected to identify the STG tendons. (**c**) Dissection of soft tissue to identify STG and remove the gastrocnemius secondary attachment. (**d**) "Push-pull" test to confirm that the STG tendons are free of attachments. (**e**) Harvest of STG using closed-end harvester to prevent premature transection of STG. (**f**) Appearance of long semitendinosus tendon obtained at harvest. (**g**) Graft preparation with graft board. Nonabsorbable 3-mm tape at the proximal end and three 2-0 FiberWire fixation at the distal end. (Alternative is tight-rope fixation device.) Running suture is used on each side of the STG graft (Reprinted from Noyes and Barber-Westin [1])

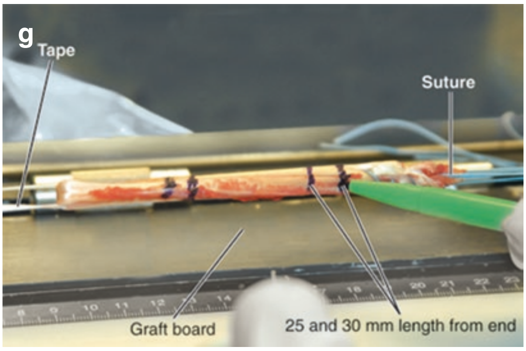


Fig. 10.2 (continued)

Table 10.4 Summary of steps to harvest a quadriceps tendon-patellar bone autograft [1]

• 5–6-cm longitudinal incision from superior pole patella, extending proximally
• Graft harvest: 10-mm wide through all 3 layers, length 60–70 cm
• Patellar bone graft: Length 22–24 mm length, diameter 9–10 mm
• Close quadriceps tendon defect with sutures
• Meticulous bone grafting patellar defect, closure soft tissues

tendon attachment in order not to weaken this site. A 10-mm wide tendon graft, through all three layers, is removed to a length of 60–70 cm (Fig. 10.3). A power saw with the cutting blade marked with paper tape to a depth of 10 mm is used to cut the anterior cortex. It is necessary to place the thin saw blade at the superior pole immediately posterior to the quadriceps tendon patella attachment to saw through the patellar bone at this location. The goal is to produce a patellar bone graft 22–24 mm long by 9–10-mm wide. The bone graft is sized to 9–10 mm in diameter. The quadriceps tendon defect is closed with interrupted 0-Ethibond suture (Ethicon, Sumerville, NJ). Two sutures of 0-nonabsorbable material are placed just proximal to the proximal patellar bone defect to create a pocket for the bone graft obtained from the coring tibia reamer. The core bone graft completely obliterates the patellar defect, and a meticulous closure of anterior tissues over the graft is performed, as already described.

10.4 ACL Anatomic Reconstruction

10.4.1 ACL Anatomy and Function Issues

Studies disagree on the division of the ACL into two distinct fiber bundles. Some authors have provided evidence of both an anatomic and functional division, whereas others doubt this division exists and argue that ACL fiber function is too complex to be artificially divided into two bundles. In some studies [31, 32], the anteromedial (AM) bundle is identified functionally at its femoral location as the proximal half of the attachment (knee in extension) that tightens with knee flexion. The posterolateral (PL) bundle is identified as the distal half of the ACL femoral attachment that tightens with knee extension. The PL bundle is described to relax with knee flexion, as the ACL femoral attachment changes from a vertical to a horizontal structure. The problem is that this description of a reciprocal tightening and relaxation of the bundles occurs only under low anterior loading conditions. With substantial anterior tibial loading, and particularly with the coupled motion of anterior translation and internal tibial rotation, the majority of the ACL fibers are brought into a load-sharing configuration to a differing percentage.

We believe the characterization of the ACL into two fiber bundles represents a gross oversimplification not supported by biomechanical studies [33, 34]. The length-tension behavior of ACL fibers is primarily controlled by the femoral attachment in reference to the center of femoral rotation, the coupled motions applied, the resting length of ACL fibers, and tibial attachment locations. Under loading conditions, fibers in both the AM and PL divisions contribute to resist tibial displacements. The function of the ACL fibers is determined by the anterior-to-posterior direction (knee at extension) as well as the proximal-to-distal femoral attachment. Placement of a graft in an anterior or posterior position may produce deleterious lengthening and graft failure.

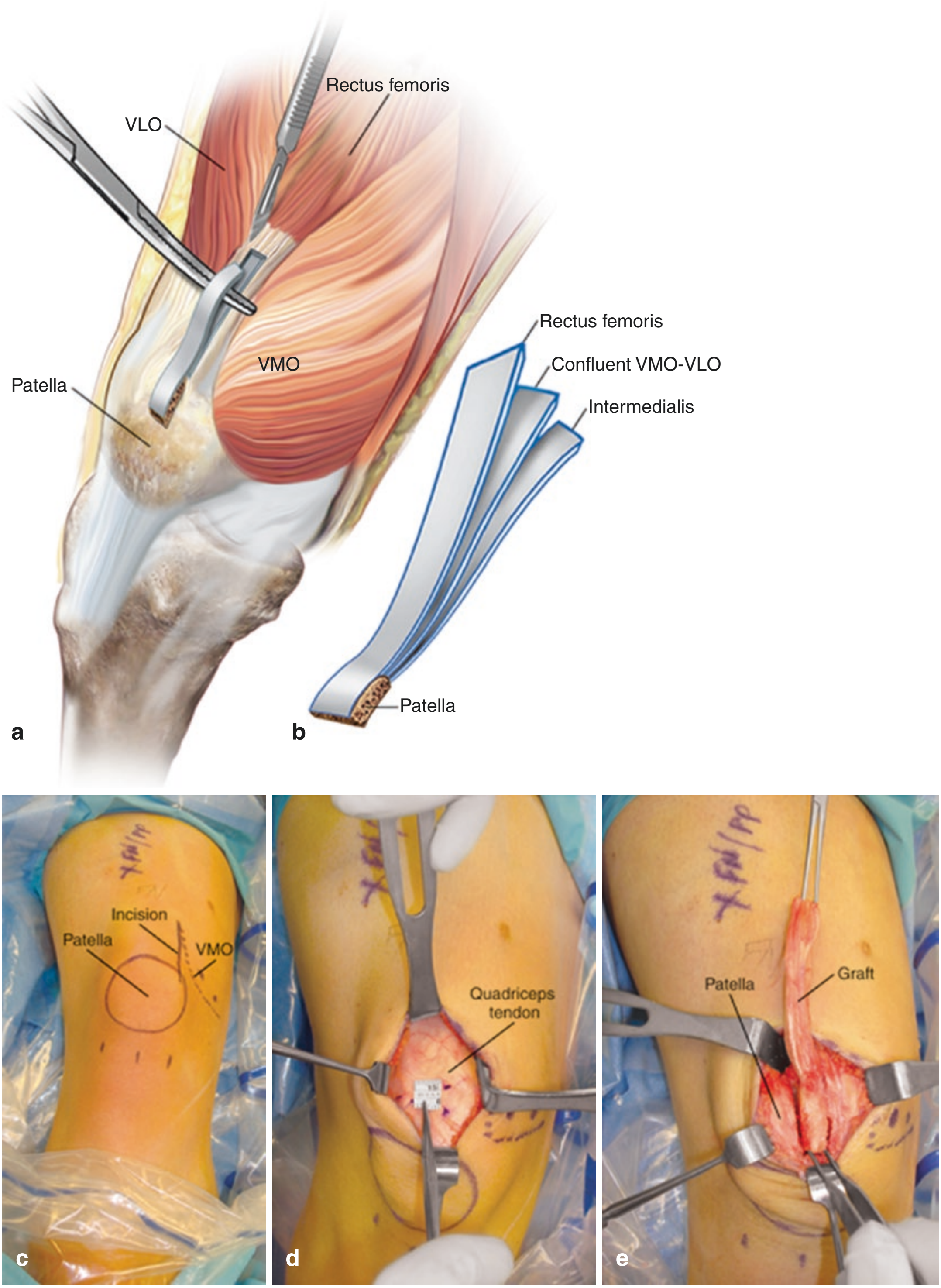


Fig. 10.3 (**a**) A quadriceps tendon graft 9- to 10-mm wide and 60–70 cm in length is removed. (**b**) Usually, all three layers are sutured together at the end of the graft (2-0 nonabsorbable suture) with a running suture on both sides of the graft. (**c**) Surgical case, initial skin incision. (**d**) Measurement of graft width. (**e**) Final harvest (Reprinted from Noyes and Barber-Westin [1])

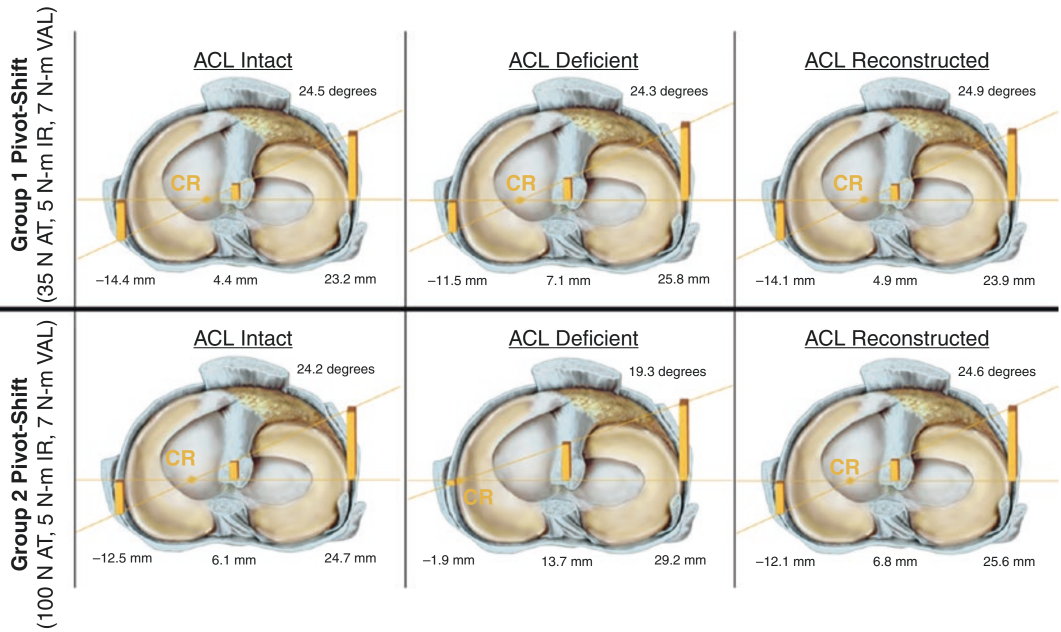


Fig. 10.4 Compartment maps of a representative specimen under two pivot-shift loading profiles for ACL-intact, ACL-deficient, and ACL-reconstructed conditions. The specimen is a right knee with the medial compartment on the left and lateral compartment on the right (*AT* anterior load, *CR* center of rotation, *IR* internal rotation, *VAL* valgus) (Reprinted from Harms et al. [38])

We conducted a series of robotic cadaveric in vitro studies on the kinematic function of the AM and PL bundles of the ACL [35–37]. The results showed both ACL bundles functioned synergistically to resist medial and lateral compartment subluxations during the simulated Lachman and pivot shift tests. In addition, a single ACL graft placed into the anatomic center of the femoral and tibial attachment sites restores normal tibiofemoral compartment translations and rotations (Fig. 10.4). The results of these studies support the recommendations in this chapter to use a single ACL graft instead of a double-bundle ACL graft construct.

10.4.2 Recommended Location and Placement of Tibial Tunnel

It is important during surgery to outline the individual size and shape of the ACL attachment for each patient. The important landmarks for the ACL tibial attachments are the medial tibial spine, posterior interspinous ridge (RER) of the proximal PCL fossa, and the attachment of the lateral meniscus. The recommended ACL tibial attachment location for a single graft is directly adjacent and anterior to the posterior edge of the lateral meniscus anterior horn attachment (Fig. 10.5). In some knees, the anterior extent of the ACL attachment may be obscured by soft tissues, and in these cases, the RER or posterior interspinous ridge of the PCL fossa is an important landmark. The center of the ACL will be 16–20 mm anterior to the RER or posterior interspinous ridge.

The guide pin is placed eccentric and 2–3 mm anterior and medial to the true ACL center, because the ACL graft displaces to the posterior and lateral aspect of the tibial tunnel [39]. The tunnel places the majority of the graft within the central tibial attachment and avoids the posterior attachment location. It is important that graft impingement against the anterior intercondylar notch does not occur because the circular graft may occupy a portion of the native flattened ACL tibial attachment. An anterior notchplasty is required, particularly in knees with an A-shaped

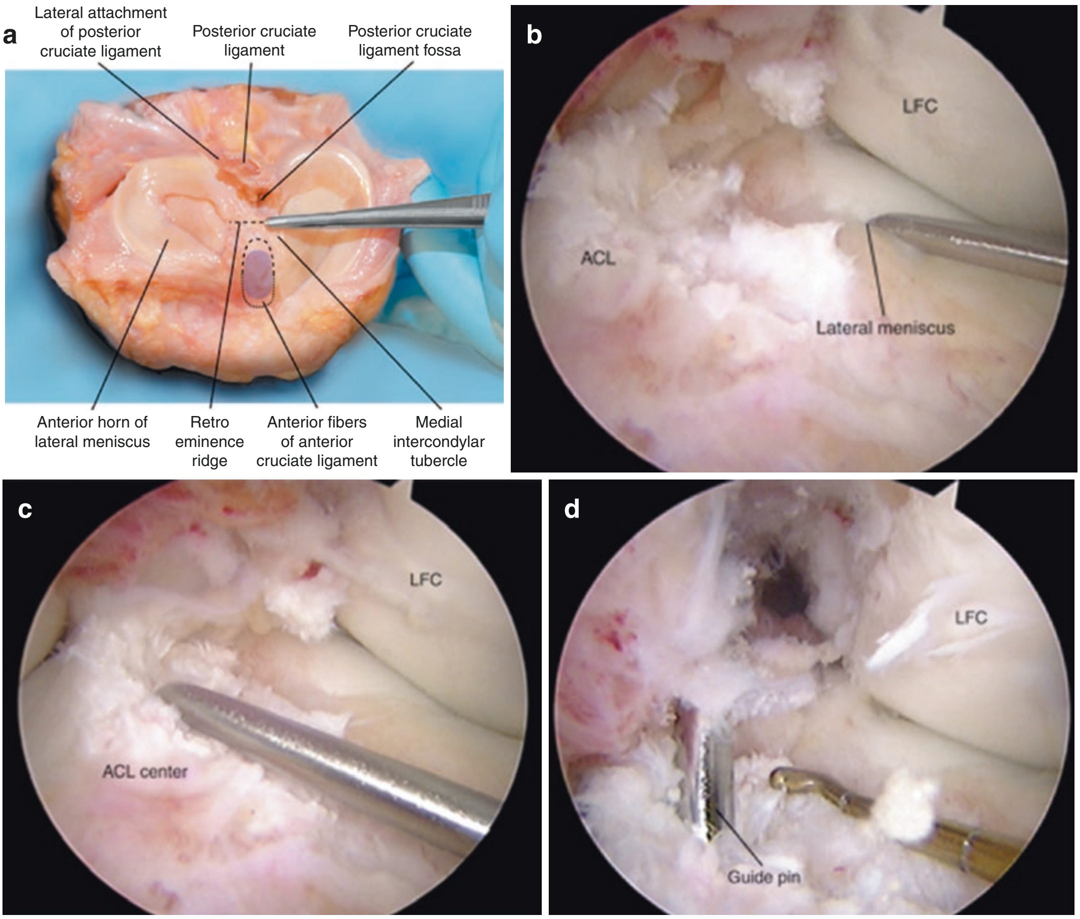


Fig. 10.5 (**a**) ACL tibial attachment is outlined along with the shaded region, indicating a central placement of an ACL graft and tibial tunnel. (**b**) Arthroscopic ACL attachment anterior to the posterior edge of the lateral meniscus. (**c**) Center of ACL attachment is marked and is anterior to the lateral meniscus posterior edge. (**d**) Placement of central guide pin for single tunnel ACL reconstruction. *FC* femoral condyle (Reprinted from Noyes and Barber-Westin [1])

notch. In order to avoid a vertical graft orientation, it is important that the tibial drill does not inadvertently penetrate into or beyond the posterior one-third ACL attachment and adjacent posterior interspinous ridge.

The tibial tunnel is placed in a coronal manner, at a 55–60° angle, allowing a tunnel length of 35–40 mm. The tunnel is begun just anterior and adjacent to the SMCL and is usually 15 mm medial to the tibial tubercle medial border and 10 mm distal to the most proximal point of the patellar tendon tibial tubercle insertion. A core reamer is placed over the guide pin to remove a tibial bone plug when a B-PT-B autograft is used to obtain a core of bone to fill the bone defects. The tunnel is drilled to the desired graft diameter, and the joint tunnel edges are chamfered to prevent graft abrasion.

10.4.3 Recommended Location and Placement of Femoral Tunnel

Important landmarks for the femoral attachment are the posterior articular cartilage, Blumensaat's line, and identification of the ACL attachment on the lateral femoral wall of the notch (Fig. 10.6). The goal is to locate the tunnel in the central to

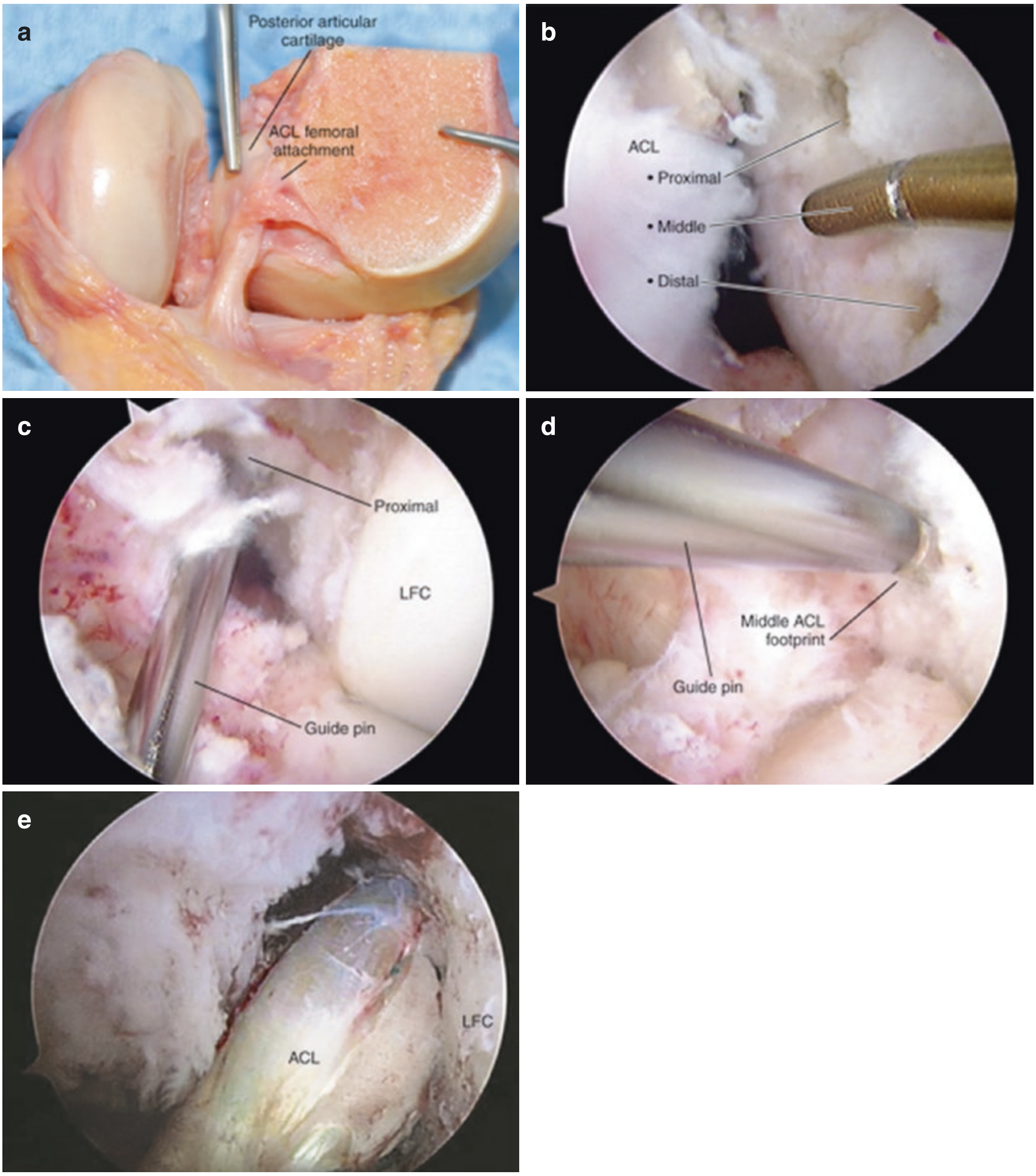


Fig. 10.6 (**a**) ACL femoral attachment at 30° knee flexion shows the entire attachment on lateral wall of notch. (**b**) Three points identified in proximal, middle, and distal portions of ACL attachment. (**c**) Transtibial guide pin placement reaches only proximal one-third of ACL attachment with a portion of the femoral tunnel extending onto the notch roof when a central ACL tibial tunnel is used. (**d**) ACL central point reached with knee hyperflexion and AM portal or with two-incision rear-entry technique. (**e**) Final graft appearance on lateral wall (Reprinted from Noyes and Barber-Westin [1])

proximal thirds to maintain ACL graft length, and within the central direct ACL native insertion that occurs through fibrocartilage and not within the posterior indirect insertion of fibers adjacent to the femoral articular cartilage edge. Piefer and colleagues [40] in a systematic review of 20 ACL femoral footprint publications arrived at recommended arthroscopic osseous landmarks on the lateral wall of the intercondylar notch which are very useful. These include, when possible, identification of the native ACL attachment, the resident's ridge or intercondylar ridge, the bifurcate ridge, the notch roof where no ACL fibers attach, and the articular cartilage junction of the lateral femoral condyle.

We recommend a central anatomic ACL placement with the femoral guide pin 2–3 mm above the midpoint of the proximal-to-distal length of the ACL attachment (30° of knee flexion) and 8 mm from the posterior articular cartilage edge (Fig. 10.5). This will produce a 10-mm tunnel in the proximal two-thirds of the ACL attachment, leaving a 3-mm thick posterior tunnel wall. The ACL attachment is defined at 20–30° of flexion with the arthroscope in the AM portal. After the femoral site is marked, the knee can be placed in 120° of flexion if an AM portal arthroscopic drilling technique is selected. A very acceptable alternative option is use of a flexible drill with the knee at 90° of flexion. A flip-cutter is also a viable technique. A 9- to 10-mm diameter tunnel occupies the proximal two-thirds of the ACL attachment. It is important that the ACL femoral tunnel not be placed too far posteriorly because this produces excessive graft tension with knee extension. In addition, the graft should not be too distal at its femoral attachment because this shortens the intra-articular graft tibiofemoral length.

A two-incision technique retrograde-drilling procedure is used if the B-PT-B graft is >90 mm and (Fig. 10.7) involves a lateral incision of 2–3 cm in length at the distal lateral femoral condyle. The posterior one-third of the ITB is incised for 4–6 cm to allow exposure. The interval posterior to the vastus lateralis is entered and the muscle protected. An S retractor is placed beneath the VLO to gently lift the muscle anteriorly, avoiding entering the proximal joint capsule. The proximal edge of the lateral femoral condyle is bluntly palpated with an instrument (over-the-top location), with the goal of locating the tunnel entrance just anterior to this point. A 15-mm periosteal incision is made and an elevator used to remove soft tissues from the site for the tunnel proximal entrance. The two-incision technique allows adjustment of graft length if required by proximal advancement in the femoral tunnel and is ideal when there is graft mismatch due to an excessively long patellar tendon. Alternatively, with a B-PT-B graft length of 80–85 mm, a FlipCutter procedure may be selected to create a femoral socket rather than a tunnel.

The ACL femoral attachment is mapped based on the bony landmarks already described. The location of the guide pin for an ACL central femoral tunnel is shown in Figs. 10.6 and 10.8. The guide pin is placed within the central ACL attachment, which is midway between the lateral notch roof and the distal articular cartilage edge, 8 mm from the posterior articular cartilage edge. With the central femoral tunnel, the posterior back wall is 3–4 mm thick and the graft occupies approximately two-thirds to three fourths of the ACL footprint. A guide pin placed 8 mm from the posterior articular cartilage at the central ACL attachment will have a 4-mm posterior back wall for an 8-mm graft and 3-mm wall for a 10-mm graft. The tunnel is drilled to the appropriate diameter, which is usually 1 mm greater than the bone portion that allows a snug graft fit in the tunnel. The edges of the tunnel are chamfered to prevent graft abrasion.

10.4.4 Graft Tunnel Passage, Conditioning, and Fixation

The graft is passed in a retrograde manner either with a Beath pin in the arthroscopic technique (placed through the accessory AM portal) or in the two-incision technique with a 20-gauge looped wire passed from the femur to the tibial tunnel. The graft is gently lifted up through the tibia and guided into the femoral tunnels with a nerve hook. The graft is marked at the bone-tendon junction to adjust its length in each tunnel. The graft is brought proximally until the bone is flush with the tibia. The femoral bone-graft plug is fixed with an interference screw of a metallic or absorbable type. Graft conditioning is performed by placing approximately 88 N tension on the distal graft sutures and flexing the knee from 0° to 135° for 30–40 flexion-extension cycles. The arthroscope is placed to verify that the graft position is ideal and there is no impingement against the lateral femoral condyle or notch with full hyperextension. Appropriate notchplasty is performed when necessary.

The knee is placed at 20° flexion, and the tension on the graft is reduced to approximately

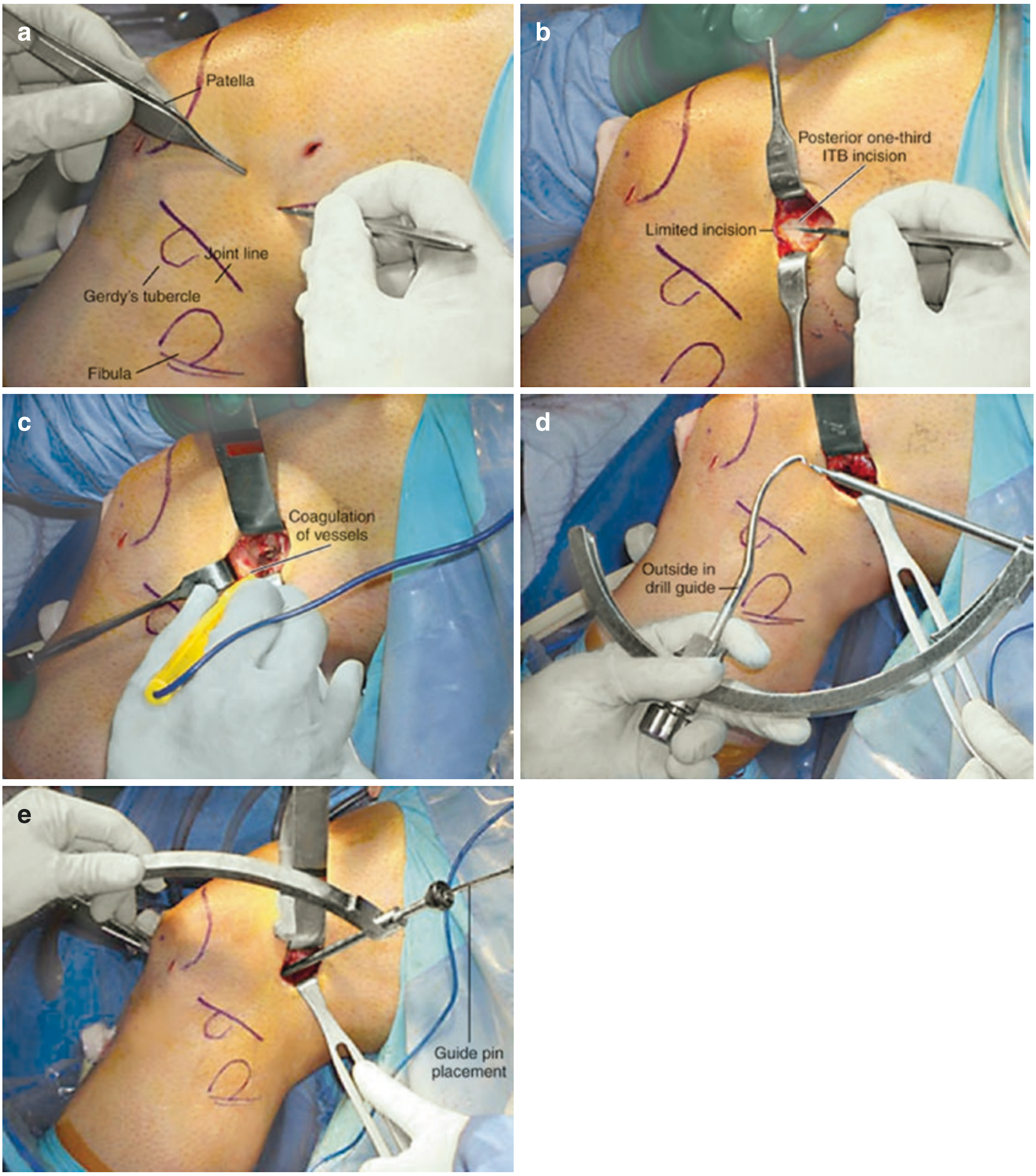


Fig. 10.7 The ACL procedure for a two-incision technique is shown. (**a**) The anatomic landmarks are shown. The joint line, tibial tubercle, and fibula are marked. (**b**) The 2-cm incision is made in the posterior one-third of the ITB, as described in the text. (**c**) Electrocoagulation of vessels. (**d**) Commercially available drill guide. (**e**) Placement of guide pin. Antegrade drilling is viewed arthroscopically (Reprinted from Noyes and Barber-Westin [1])

10–15 N in order to avoid overconstraining AP tibial translation. A finger is placed on the anterior tibia to maintain the posterior gravity position of the tibia. An interference screw is placed. In cases where the interference screw fixation is not ideal or the screw resistance on placement is not acceptable, the sutures are tied over a suture post. The arthroscope is placed into the joint and final graft inspection performed. A Lachman test is performed, and there should be total AP translation motion of 3 mm, indicating that the graft has not been over-tightened. If the graft

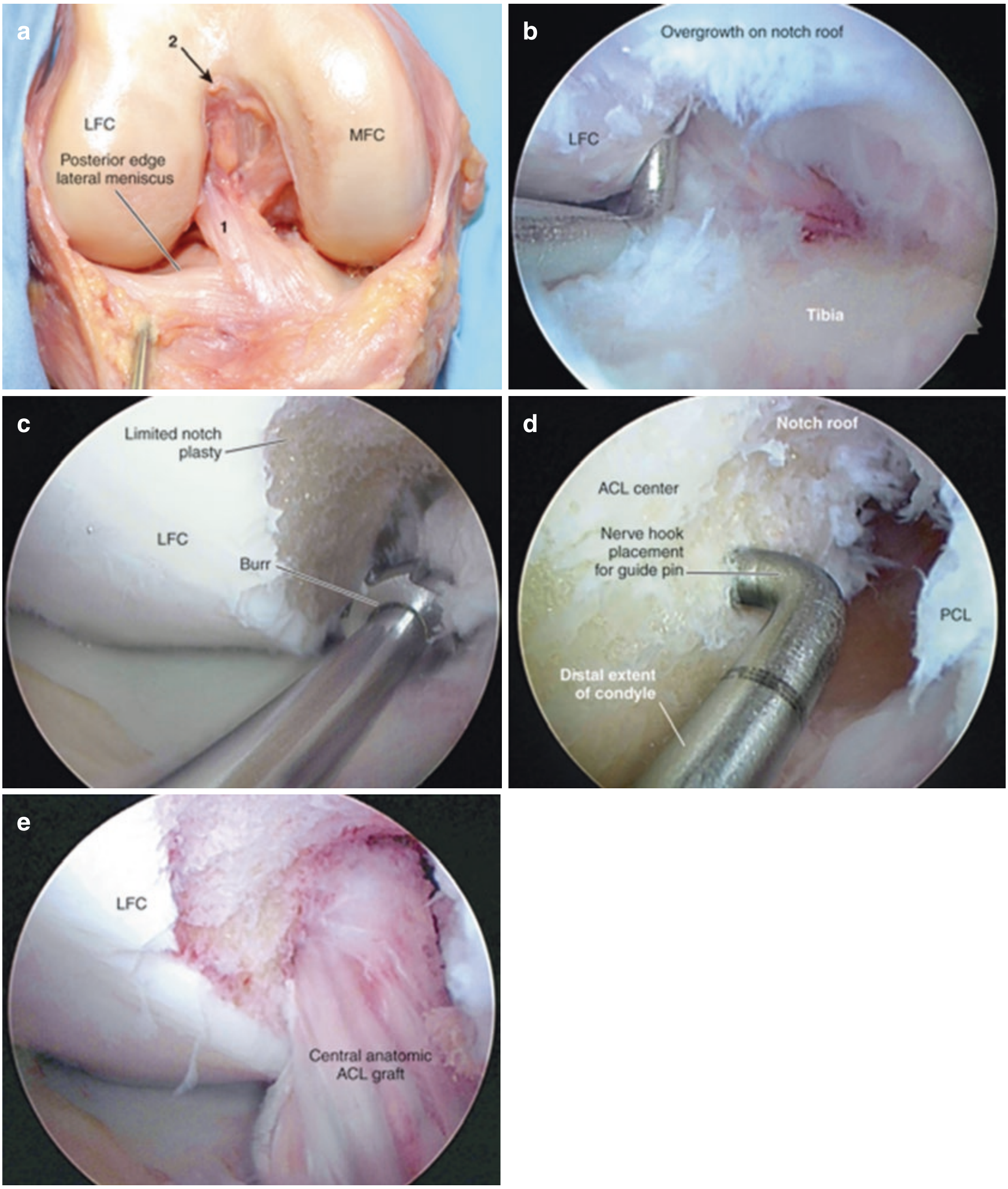


Fig. 10.8 (**a**) A normal femoral notch is shown, which is viewed at arthroscopy by using the AM portal. 1 shows the normal space between the medial femoral condyle and the PCL which is occupied by the ACL. 2 shows the normal anterior notch that should not impinge on the graft. (**b**) Revision ACL with failed ACL graft shows overgrowth of the lateral notch and notch roof, requiring a limited notchplasty. (**c**) The lateral notch wall is visualized entirely posteriorly to the articular cartilage of the femoral condyle. (**d**) The ACL femoral attachment is mapped out, and a central small hole is made for placement of the guide pin. The resident's ridge has been removed. The anterior notch region has not been disturbed. (**e**) Final placement of a single-bundle graft within a central anatomic tibial and femoral placement that occupies over 75% of the attachment site (Reprinted from Noyes and Barber-Westin [1])

has a “bowstring”, tight appearance with little to no anterior tibial translation on testing, the distal tensioning and fixation procedure is repeated with less tension placed on the graft.

10.4.5 Technique Using STG Graft

When a STG graft is selected, the same procedure is used with the following exception. In the two-incision technique, a femoral post is used with the sutures tied first at the femoral site about the post (35 mm, 4.0-mm cancellous self-cutting screw with washer). An absorbable interference screw is added. At the tibia, the interference screw is first placed, followed by the suture post fixation. Using the combined interference screw and suture post provides sufficient graft strength fixation for rehabilitation to proceed equal to the B-PT-B graft. An alternative technique for a four-strand STG graft using a FlipCutter (Fig. 10.9) and EndoButton

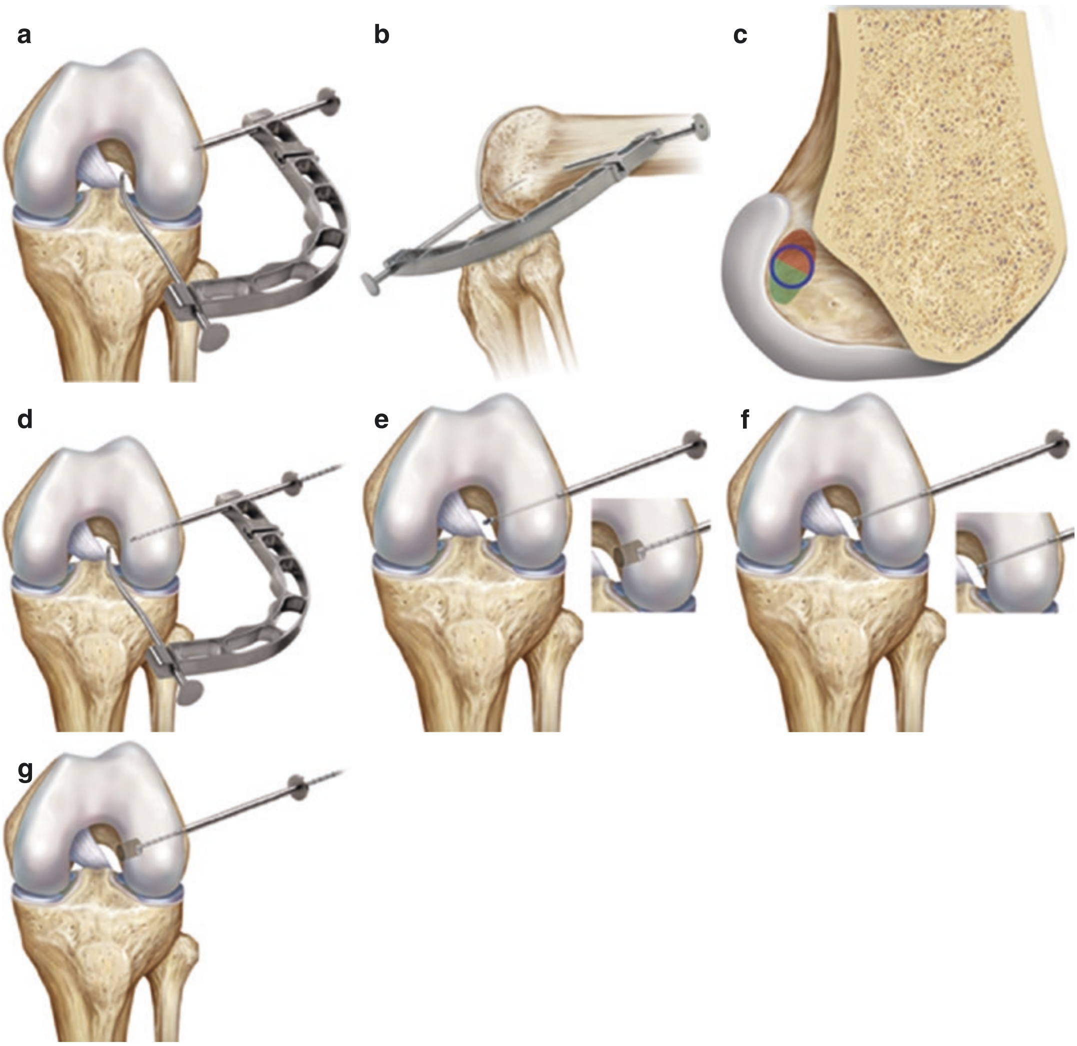


Fig. 10.9 Demonstration of FlipCutter technique for femoral socket or tunnel. (**a, b**) Placement and location of drill guide. (**c**) Central ACL anatomic tunnel placement. (**d**) Placement of the FlipCutter. (**e**) The FlipCutter is advanced at the femoral attachment. (**f**) The drill end is “flipped” at a right angle to the pin. (**g**) Creation of a femoral socket that can extend completely as a tunnel if desired. (This image provided courtesy of Arthrex, Inc., Naples, FL) (Reprinted from Noyes and Barber-Westin [1])

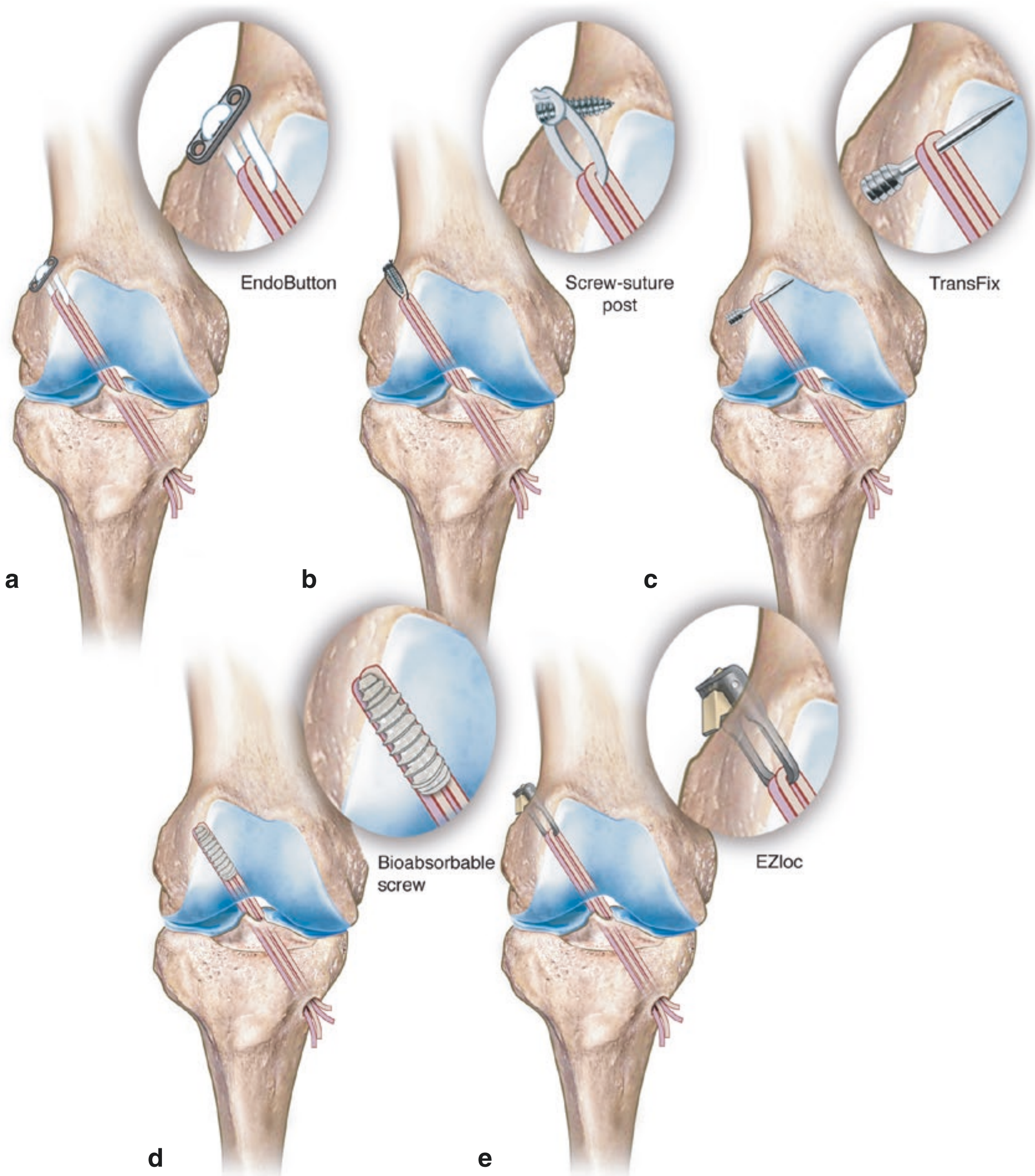


Fig. 10.10 (**a**–**e**)A variety of ACL femoral fixation techniques for STG grafts. The interference screw alone (**d**) is not recommended because it produces the lowest graft tensile strength to pull-out (Reprinted from Noyes and Barber-Westin [1])

or TightRope technique is described elsewhere [1]. A variety of techniques for femoral fixation (Fig. 10.10) and tibial fixation (Fig. 10.11) are available, based on the preference of the surgeon. Interference screw fixation alone is not recommended. A suture post is commonly required to achieve higher strength graft fixation.

Robust graft conditioning is required before final fixation to remove abnormal graft elongations in the postoperative period. Biomechanical studies in knee joints using robotic technology in our laboratory show that an 88-N tensile load applied from 0 to 120° for 40 cycles is necessary (Fig. 10.12). The graft board static conditioning alone does not provide adequate graft conditioning.

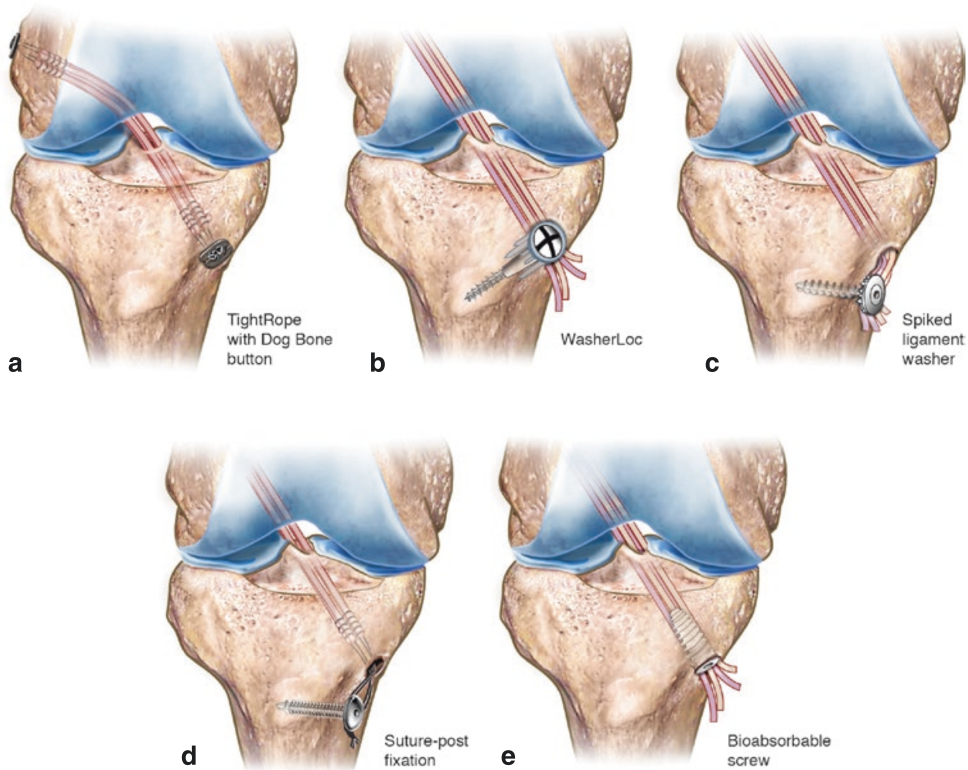


Fig. 10.11 (**a**–**e**) Various tibial fixation techniques for STG grafts. An interference screw alone (**d**) is not recommended (Reprinted from Noyes and Barber-Westin [1])

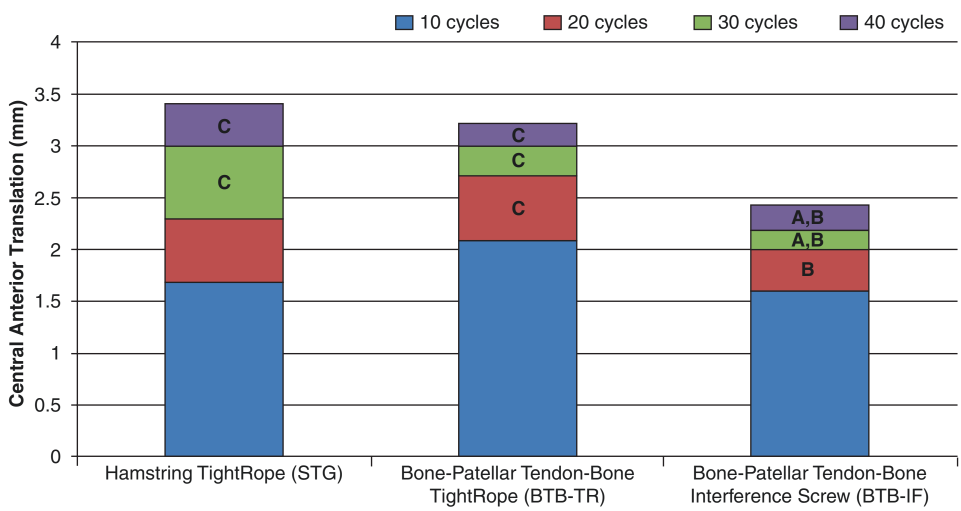


Fig. 10.12 Increase in knee anterior tibial translation with each ACL graft reconstruction during the flexion-extension conditioning cycles. The measurements were calculated at 25° knee flexion. This represents the graft elongation that occurs after graft-board pre-tensioning alone and indicates that this conditioning mechanism is ineffective in producing a steady-state graft. (**a**) Significantly different from hamstring TightRope (STG) graft (within the same cycle; $P < 0.05$). (**b**) Significantly different from bone-patellar tendon-bone TightRope (BPTB-TR) graft (within the same cycle; $P < 0.05$). (**c**) Significantly different from bone-patellar tendon-bone interference screw (BPTB-IF) graft (within the same cycle; $P < 0.05$)

10.4.5.1 Critical Points

ACL Anatomy

- Characterization of ACL into two fiber bundles represents a gross oversimplification not supported by biomechanical studies.
- A single ACL graft placed into the anatomic center of the femoral and tibial attachment sites restores normal tibiofemoral compartment translations and rotations.

Tibial Tunnel

- Recommended tibial attachment location is directly adjacent and anterior to the posterior edge of the lateral meniscus anterior horn attachment.
- Place guide pin eccentric and 2–3 anterior and medial to true ACL center.
- Place tibial tunnel in coronal manner, 55–60° angle, tunnel length 35–40 mm.
- Use core reamer to obtain good quality bone to fill bone defects.
- Drill tunnel, chamfer edges.

Femoral Tunnel

- Two-incision technique: drill tunnel retrograde through lateral incision 2–3 cm at distal lateral femoral condyle.
- Perform femoral notchplasty to avoid graft impingement.
- Identify ACL attachment with knee in 20–30° flexion, scope in anteromedial portal.
- Place guide pin within central ACL attachment. Preserve 3–4 mm of posterior back wall of the tunnel so that the graft is not placed too far posteriorly.
- Drill tunnel, chamfer edges.

Graft Tunnel Passage, Conditioning, and Fixation

- Pass graft gently in retrograde arthroscopically assisted.
- Bring graft proximally until bone is flush with tibia.
- Femoral position of graft at or just proximal to inside femoral tunnel.
- Fix femoral bone graft plug with interference screw.
- Condition graft: 44 N tension, flex knee 0–135°, 40 cycles.
- Verify position arthroscopically, no impingement.
- Place knee in 20° flexion, reduce tension to 10–15 N.
- Place interference screw tibia. Use additional sutures tied over suture post if required.
- Perform Lachman test, ensure no overconstraint.
- For STG graft, femoral fixation: post with sutures and absorbable interference screw if necessary. Tibial fixation: interference screw plus suture post.
- Robust STG graft conditioning: 88 N tension, flex knee 0–120°, 40 cycles.

10.5 Authors' ACL Reconstruction Clinical Studies

We published a series of prospective clinical studies on ACL primary reconstruction in over 650 knees with acute, subacute, and chronic ruptures (Table 10.5) [28, 41–57] The data from these investigations provide information regarding the following variables on clinical outcome: (1) type of graft, (2) sterilization of allografts, (3) gender, (4) chronicity of injury, (5) concomitant operative procedures, (6) preexisting joint arthritis, (7) varus osseous malalignment, (8) the rehabilitation program, and (9) type of insurance (workers' compensation vs. private). A summary of the outcomes from our primary ACL reconstruction investigations is shown in Table 10.6.

10.6 Treatment of Meniscus Tears

Studies have shown that, regardless of the outcome of ACL reconstruction in terms of restoration of knee stability, meniscectomy accelerates degenerative joint changes [14, 58–64]. Nearly every long-term study has reported a statistically significant correlation between meniscectomy performed either concurrently or after the ACL reconstruction and moderate-to-severe radiographic evidence of osteoarthritis. We conducted a systematic review of the treatment of meniscus tears during ACL reconstruction of studies published from 2001 to 2011 [65]. Data on 11,711 meniscus tears (in 19,531 patients) from

Table 10.5 Summary of authors' primary ACL reconstruction clinical studies

Study citation	Demographic data, graft type, allograft sterilization	KT-2000 total AP displacement (I-N) at fu <3 mm (%)	3–5 mm (%)	>5 mm (%)	Return to sports
Noyes [41]	*Acute ACL tears, 5–9 years fu*				47% preinjury level, 36% lower level, 13% no sports non-knee-related factors, 4% no sports knee-related problems
	Fascia lata allografts: fresh-frozen (*n* = 28)	77	20	3	
	Fascia lata allografts: freeze-dried (*n* = 40)	75	20	5	
Noyes, Barber-Westin [42]	*Chronic ACL tears, 2–4.5 years fu*				Compared with preoperative level: 66% increased level, 7% same level, 7% lower level, 16% playing with symptoms, 3% no sports non-knee-related factors, 13% no sports knee-related problems
	B-PT-B allografts: fresh-frozen (*n* = 54)	53	31	16	
	B-PT-B allografts: irradiated (*n* = 10)	60	10	30	
	B-PT-B allografts + ITB EA, fresh-frozen (*n* = 40)	74	23	3	
Noyes, Barber-Westin [43]	*Chronic ACL tears, 2–3.4 years fu* B-PT-B allografts + LAD, irradiated (*n* = 49)	53	30	17	Compared with preoperative level: 65% increased level, 10% same level, 4% lower level, 7% playing with symptoms, 7% no sports non-knee-related factors, 7% no sports knee-related problems
Noyes, Barber-Westin [44]	*Acute* vs. *chronic ACL tears, 2–3 years fu*				Acutes: 50% preinjury level, 3% increased level, 27% lower level, 3% playing with symptoms, 17% no sports non-knee-related factors Chronics compared with preoperative level: 54% increased level, 9% same level, 12% lower level, 11% playing with symptoms, 2% no sports non-knee-related factors, 12% no sports knee-related problems
	B-PT-B autografts chronic ACL tears (*n* = 57)	84	12	4	
	B-PT-B autografts acute ACL tears (*n* = 30)	92	4	4	
Barber-Westin [45]	*Male* vs. *female ACL reconstruction, 2–3 years fu*				Acutes: 45% preinjury level, 5% increased level, 33% lower level, 2% playing with symptoms, 15% no sports non-knee-related factors Chronics compared with preoperative level: 52% increased level, 11% same level, 15% lower level, 5% playing with symptoms, 11% no sports non-knee-related factors, 5% no sports knee-related problems
	B-PT-B autografts men (*n* = 47)	80	16	4	
	B-PT-B autografts women (*n* = 47)	87	8	5	
Noyes, Barber-Westin [46]	*Chronic ACL tears, 2–3.6 years fu* B-PT-B autografts (*n* = 53)	79	16	5	Compared with preoperative level: 66% increased level, 6% same level, 7% lower level, 6% no sports non-knee-related factors, 15% no sports knee-related problems

AP anteroposterior, *B-PT-B* bone-patellar tendon-bone, *EA* extra-articular, *fu* follow-up, *ITB* iliotibial band, *I-N* involved-noninvolved

159 studies showed that 65% were treated by meniscectomy; 26%, by repair; and 9%, by no treatment. This was concerning because many meniscus tears can be successfully treated by repair, thereby salvaging this important structure.

We have long advocated repair of meniscus tears instead of resection, assuming the appropriate indications are met [3, 57, 66–68]. Our indications for meniscus repair are shown below:

1. Meniscus tear with tibiofemoral joint line pain
2. Patient <50 years old, or physically active patient <60 years old
3. Concurrent knee ligament reconstruction or osteotomy
4. Meniscus tear reducible, good tissue integrity, will retain normal position in the joint once repaired

Table 10.6 Summary of conclusions from authors' primary ACL reconstruction clinical studies [1]

Factor	Conclusions
Type of graft	B-PT-B autografts preferred whenever possible, decreased failure rate in chronic knees, more rapid graft healing. Autografts provide higher success rate in subjective, objective, and functional parameters. Allografts reserved for multiligament surgery, knee dislocations, special situations
Augmentation procedures for allografts	ITB extra-articular procedure decreases allograft failure rate in chronic knees, recommended in grossly unstable knees (grade 3 pivot shift)
Secondary sterilization of allografts	Irradiation most likely deleterious, increase in failure rate, not recommended
Gender	No difference in outcomes between males and females. No scientific basis to use gender as selection criteria for reconstruction
Chronicity of injury	No difference between acute and chronic knee injuries in objective stability after B-PT-B autograft reconstruction Significantly poorer results in chronic knees for symptoms, limitations with sports and daily activities, and patient rating of knee condition owing to loss of meniscus tissue, preexisting joint damage Reconstruct ACL early after injury in active patients
Concomitant operative procedures	Meniscus repairs frequent, results may be improved by concomitant ACL reconstruction. High success rates, even in complex tears extending into central third region, regardless of patient age Posterolateral injuries frequently accompanied by ACL ruptures – reconstruct all ligamentous ruptures concurrently MCL injuries usually do not require surgical treatment unless gross instability exists
Preexisting joint arthrosis	Symptomatic unstable knees can be improved by ACL reconstruction. Advise return low-impact activities
Varus osseous malalignment	ACL reconstruction usually staged after osteotomy in symptomatic unstable knees. ACL reconstruction not required after osteotomy in knees that are asymptomatic, willing to modify activities
Rehabilitation program	Immediate motion and rehabilitation safe, not deleterious to healing graft, low incidence (<1%) of arthrofibrosis. Identify and immediately treat limitation of knee motion with overpressure program. Full motion regained within weeks of surgery (with exception of PCL reconstructions in which hyperflexion is delayed)
Insurance	No difference in outcome between workers' compensation and privately insured patients except days of lost employment. Reconstruct workers' compensation patients earlier after injury

B-PT-B bone-patellar tendon-bone, *ITB* iliotibial band, *MCL* medial collateral ligament, *PCL* posterior cruciate ligament

5. Peripheral single longitudinal tears: red–red, 1 plane, repairable in all cases, high success rates
6. Middle one-third tears: red-white (vascular supply present), often repairable with good success rates
7. Red-white single plane outer-third and middle-third tears (longitudinal, radial, horizontal): often repairable if good tissue quality
8. Outer-third and middle-third tears (complex, double longitudinal, triple longitudinal, flap): repair versus excision
9. Red-white, multiple planes: repair versus excision
10. Meniscus root tears: repair if not degenerative

Meniscus tears suitable for repair are located in either the periphery or at the junction of the middle and outer third regions where a blood supply is retained. Complex tears are evaluated on an individual basis for repair potential. The repair may require an accessory posteromedial (Fig. 10.13) or posterolateral (Fig. 10.14) approach for exposure to tie the sutures using an inside-out suture technique. A meticulous vertical divergent suture technique is favored in which multiple sutures are passed through both the superior and inferior surfaces of the meniscus (Fig. 10.15). All-inside suture-based meniscus repair devices are also available which are ideal for red/white longitudinal tears and root

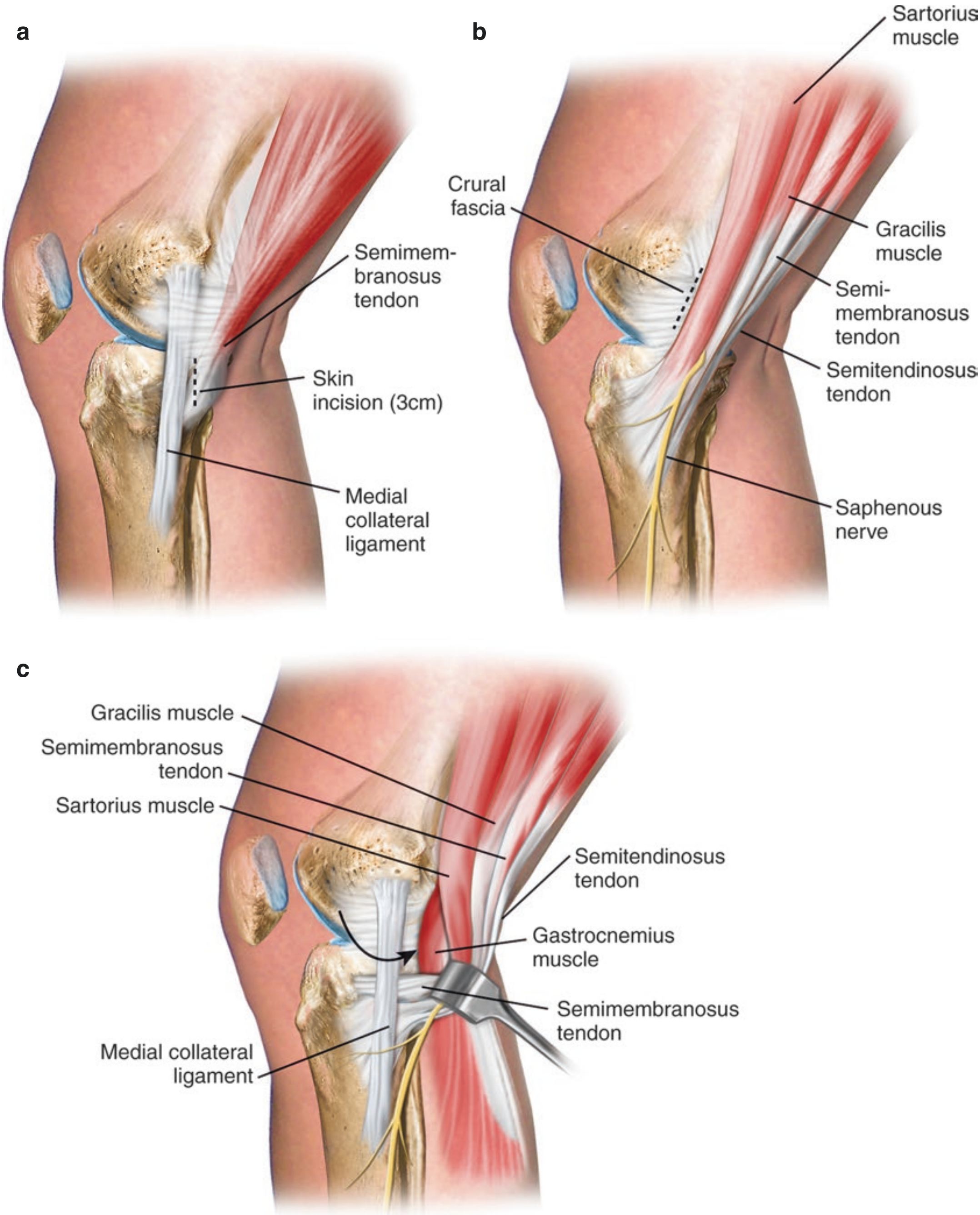


Fig. 10.13 The accessory posteromedial approach is shown for a medial meniscus repair. (**a**) Site of the posteromedial skin incision. (**b**) The incision is shown through the anterior portion of the sartorius fascia. (**c**) The interval is opened between the posteromedial capsule and the gastrocnemius tendon, just proximal to the semimembranosus tendon (*arrow*). The fascia over the semimembranosus tendon is excised to its tibial attachment to facilitate retrieval of the posterior meniscus sutures (Reprinted from Noyes and Barber-Westin [66])

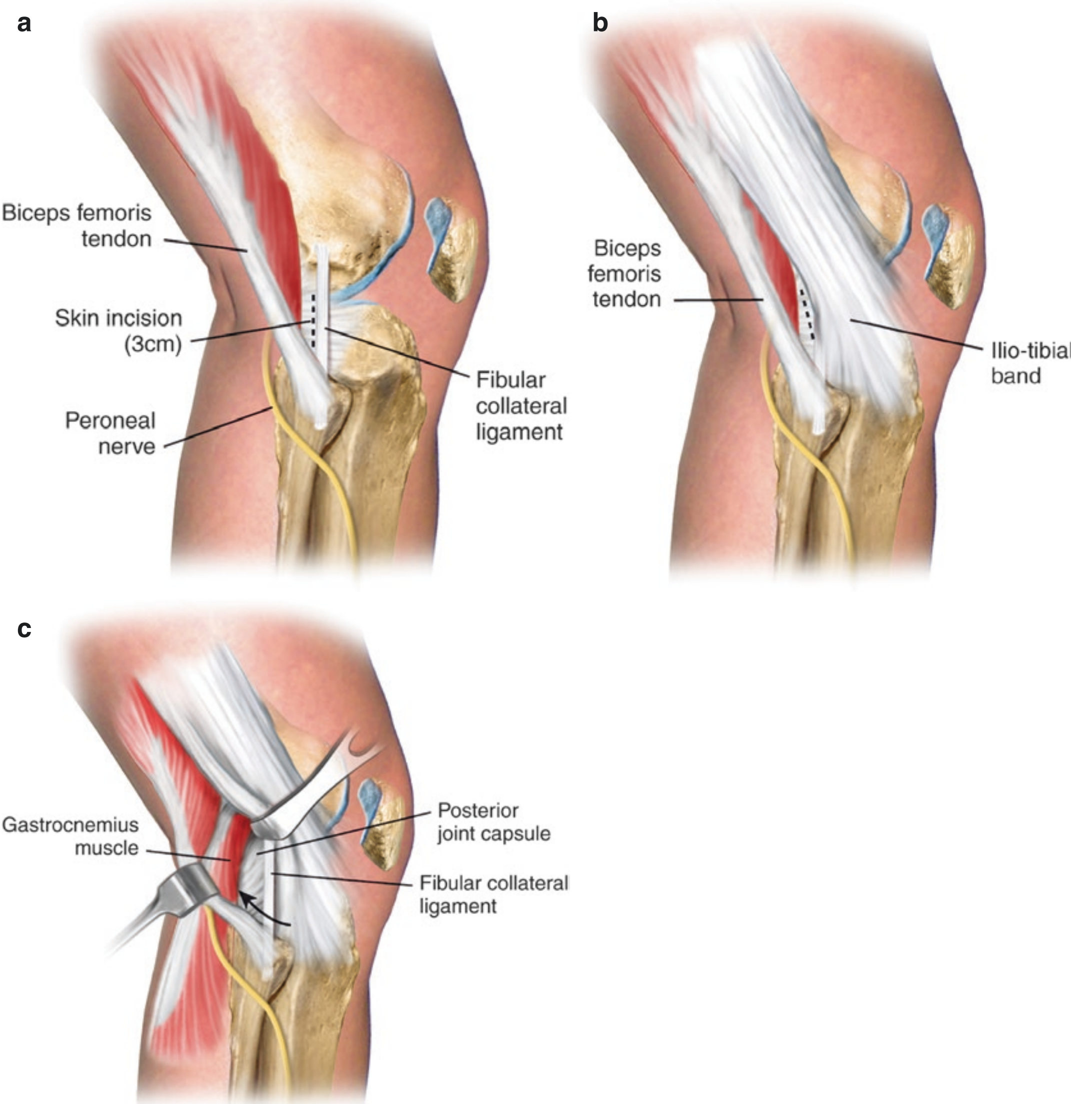


Fig. 10.14 (**a**) Site of the posterolateral incision for a lateral meniscus repair. (**b**) Incision site in the interval between the posterior edge of the iliotibial band and the anterior edge of the biceps tendon. (**c**) The interval between the lateral gastrocnemius and posterolateral capsule is opened bluntly, just proximal to the fibular head, avoiding entering the joint capsule (Reprinted from Noyes and Barber-Westin [66])

tears (Fig. 10.16). The postoperative rehabilitation programs allows immediate knee motion and early weight bearing but protects the repairs by not allowing squatting, kneeling, or running for 4–6 months [69].

We have conducted several clinical studies to determine the outcome of meniscus repairs [57, 67, 68, 70, 71]. In one study, 198 meniscus repairs in 177 patients were followed 2–9.6 years postoperatively [68]. All of the tears extended into the red-white zone or had a rim width ≥4 mm. At follow-up, 80% of the patients had not required additional surgery and had no tibiofemoral symptoms related to the repair. These results were verified more recently in a systematic review we conducted of 23 investigations in which menis-

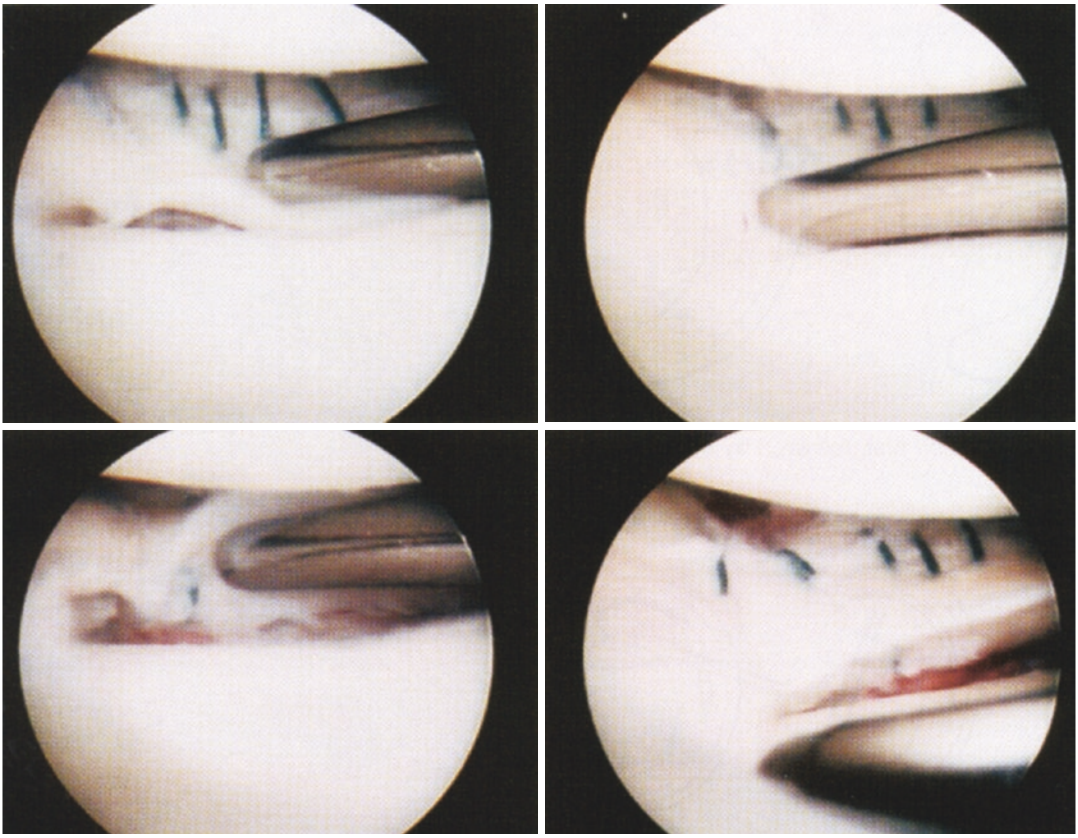


Fig. 10.15 Meniscus repair instead of meniscectomy to preserve knee joint function. A longitudinal meniscal tear site demonstrates some fragmentation inferiorly. This tear required multiple superior and inferior vertical divergent sutures to achieve anatomic reduction (Reprinted from Noyes and Barber-Westin [67])

cus repairs for tears in the red-white zone were performed [72]. There were 767 repairs, of which 78% were done with an ACL reconstruction. Overall, 83% of these repairs were considered clinically healed.

We conducted a long-term study (10–22 years) of single longitudinal meniscus repairs that extended into the central region in patients ≤20 years of age [3]. Twenty-nine repairs were evaluated; 18 by follow-up arthroscopy, 19 by clinical evaluation, 17 by MRI, and 22 by weight-bearing posteroanterior radiographs. A 3 Telsa MRI scanner with cartilage-sensitive pulse sequences was used and T2 mapping was performed. Eighteen (62%) of the meniscus repairs had normal or nearly normal characteristics. Six (21%) repairs required arthroscopic resection; two had loss of joint space on radiographs, and three that were asymptomatic failed according to MRI criteria. There was no significant difference in the mean T2 scores in the menisci that had not failed between the involved and contralateral tibiofemoral compartments. There were no significant differences between the initial and long-term evaluations for pain, swelling, jumping, patient knee condition rating, or the Cincinnati rating score. The majority of patients were participating in sports without problems, which did not affect the failure rate. The outcomes support the recommendation in younger active patients to spend as much time and attention to a meniscus repair as a concurrent ACL reconstruction, as the eventual function of the knee joint is equally dependent on the success of both structures (Fig. 10.17).

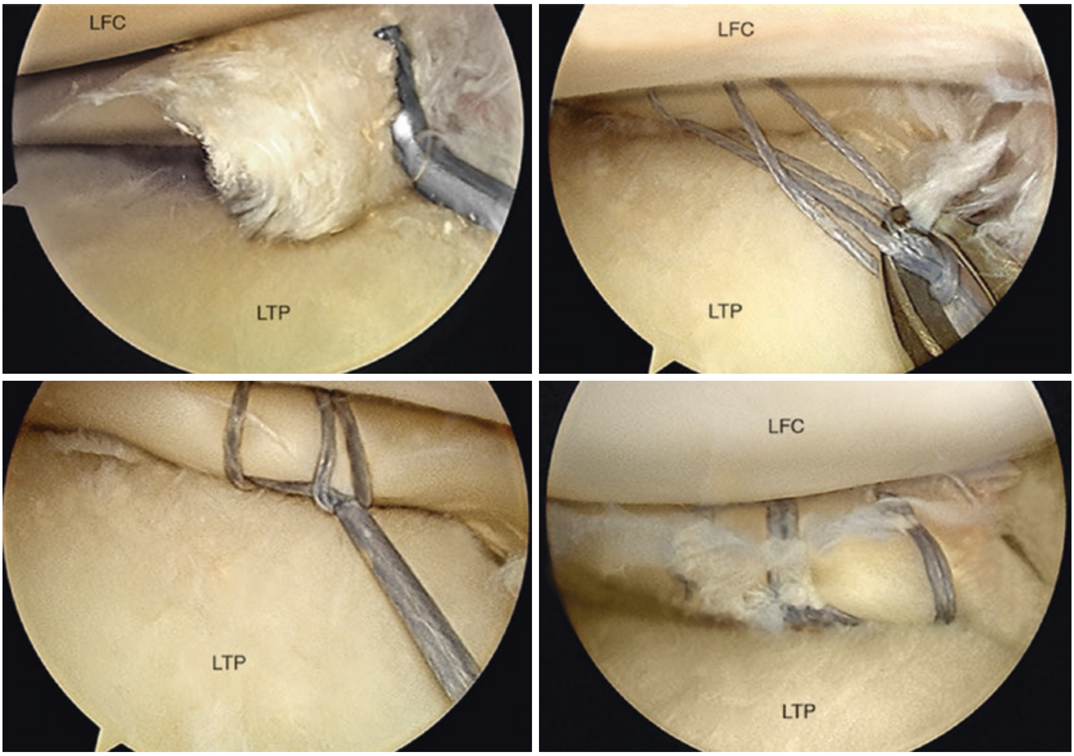


Fig. 10.16 Arthroscopic visualization of a lateral meniscus root tear (**a**). A double locking loop stitch (NovoStitch, Ceterix) is placed through the meniscus at the tear site (**b**). Three loop stitches were used to achieve a high strength fixation (**c**). Final configuration of the lateral meniscus repair with the meniscus pulled flush to the repair site (**d**) (Reprinted from Noyes and Barber-Westin [66])

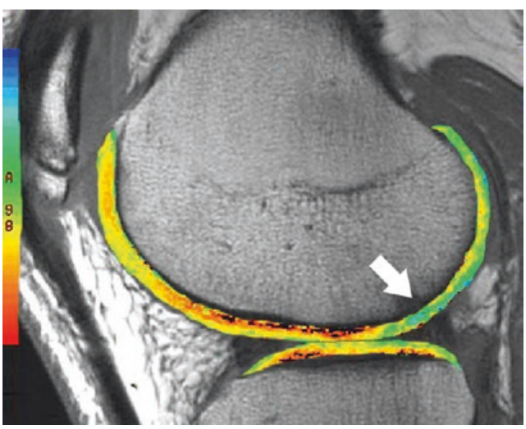


Fig. 10.17 T2 magnetic resonance imaging of a 37-year old male 17 years post-ACL reconstruction and lateral meniscus repair. The patient was asymptomatic with light sports activities. The lateral meniscus repair healed and the ACL reconstruction restored normal stability. Prolongation of T2 values is noted over the posterior margin with adjacent subchondral sclerosis (*arrow*) (Reprinted from Noyes et al. [3])

References

1. Noyes FR, Barber-Westin SD. Anterior cruciate ligament primary reconstruction: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 137–220. https://doi.org/10.1016/B978-0-323-32903-3.00007-X.
2. Potter HG, Foo LF. Magnetic resonance imaging of articular cartilage: trauma, degeneration, and repair. Am J Sports Med. 2006;34(4):661–77. https://doi.org/10.1177/0363546505281938.
3. Noyes FR, Chen RC, Barber-Westin SD, Potter HG. Greater than 10-year results of red-white longitudinal meniscal repairs in patients 20 years of age or younger. Am J Sports Med. 2011;39(5):1008–17. https://doi.org/10.1177/0363546510392014.
4. Everhart JS, Best TM, Flanigan DC. Psychological predictors of anterior cruciate ligament reconstruction outcomes: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2015;23(3):752–62. https://doi.org/10.1007/s00167-013-2699-1.

5. Rosenberg TD, Scott SM, Coward DB, Dunbar WH, Ewing W, Johnson CL, Paulos LE. Arthroscopic meniscal repair evaluated with repeat arthroscopy. Arthroscopy. 1986;2(1):14–20.
6. DeHaven KE, Lohrer WA, Lovelock JE. Long-term results of open meniscal repair. Am J Sports Med. 1995;23(5):524–30.
7. Muellner T, Egkher A, Nikolic A, Funovics M, Metz V. Open meniscal repair: clinical and magnetic resonance imaging findings after twelve years. Am J Sports Med. 1999;27(1):16–20.
8. Chalmers PN, Mall NA, Moric M, Sherman SL, Paletta GP, Cole BJ, Bach BR Jr. Does ACL reconstruction alter natural history? A systematic literature review of long-term outcomes. J Bone Joint Surg Am. 2014;96(4):292–300. https://doi.org/10.2106/JBJS.L.01713.
9. Louboutin H, Debarge R, Richou J, Selmi TA, Donell ST, Neyret P, Dubrana F. Osteoarthritis in patients with anterior cruciate ligament rupture: a review of risk factors. Knee. 2009;16(4):239–44. https://doi.org/10.1016/j.knee.2008.11.004.
10. Claes S, Hermie L, Verdonk R, Bellemans J, Verdonk P. Is osteoarthritis an inevitable consequence of anterior cruciate ligament reconstruction? A meta-analysis. Knee Surg Sports Traumatol Arthrosc. 2013;21(9):1967–76. https://doi.org/10.1007/s00167-012-2251-8.
11. Mather RC 3rd, Koenig L, Kocher MS, Dall TM, Gallo P, Scott DJ, Bach BR Jr, Spindler KP, Group MK. Societal and economic impact of anterior cruciate ligament tears. J Bone Joint Surg Am. 2013;95(19):1751–9. https://doi.org/10.2106/JBJS.L.01705.
12. Noyes FR, Barber-Westin SD. 17 - Posterolateral ligament injuries: diagnosis, operative techniques, and clinical outcomes. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 527–77. https://doi.org/10.1016/B978-0-323-32903-3.00017-2.
13. Linclau L. Measuring patellar height. Acta Orthop Belg. 1984;50:70–4.
14. Gerhard P, Bolt R, Duck K, Mayer R, Friederich NF, Hirschmann MT. Long-term results of arthroscopically assisted anatomical single-bundle anterior cruciate ligament reconstruction using patellar tendon autograft: are there any predictors for the development of osteoarthritis? Knee Surg Sports Traumatol Arthrosc. 2013;21(4):957–64. https://doi.org/10.1007/s00167-012-2001-y.
15. Pallis M, Svoboda SJ, Cameron KL, Owens BD. Survival comparison of allograft and autograft anterior cruciate ligament reconstruction at the United States military academy. Am J Sports Med. 2012;40(6):1242–6. https://doi.org/10.1177/0363546512443945.
16. Lebel B, Hulet C, Galaud B, Burdin G, Locker B, Vielpeau C. Arthroscopic reconstruction of the anterior cruciate ligament using bone-patellar tendon-bone autograft: a minimum 10-year follow-up. Am J Sports Med. 2008;36(7):1275–82. https://doi.org/10.1177/0363546508314721.
17. Sanders TL, Pareek A, Hewett TE, Levy BA, Dahm DL, Stuart MJ, Krych AJ. Long-term rate of graft failure after ACL reconstruction: a geographic population cohort analysis. Knee Surg Sports Traumatol Arthrosc. 2017;25(1):222–8. https://doi.org/10.1007/s00167-016-4275-y.
18. Webster KE, Feller JA, Hartnett N, Leigh WB, Richmond AK. Comparison of patellar tendon and hamstring tendon anterior cruciate ligament reconstruction: a 15-year follow-up of a randomized controlled trial. Am J Sports Med. 2016;44(1):83–90. https://doi.org/10.1177/0363546515611886.
19. Bottoni CR, Smith EL, Shaha J, Shaha SS, Raybin SG, Tokish JM, Rowles DJ. Autograft versus allograft anterior cruciate ligament reconstruction: a prospective, randomized clinical study with a minimum 10-year follow-up. Am J Sports Med. 2015;43(10):2501–9. https://doi.org/10.1177/0363546515596406.
20. Barrett AM, Craft JA, Replogle WH, Hydrick JM, Barrett GR. Anterior cruciate ligament graft failure: a comparison of graft type based on age and Tegner activity level. Am J Sports Med. 2011;39(10):2194–8. https://doi.org/10.1177/0363546511415655.
21. Kane PW, Wascher J, Dodson CC, Hammoud S, Cohen SB, Ciccotti MG. Anterior cruciate ligament reconstruction with bone-patellar tendon-bone autograft versus allograft in skeletally mature patients aged 25 years or younger. Knee Surg Sports Traumatol Arthrosc. 2016;24(11):3627–33. https://doi.org/10.1007/s00167-016-4213-z.
22. Kraeutler MJ, Bravman JT, McCarty EC. Bone-patellar tendon-bone autograft versus allograft in outcomes of anterior cruciate ligament reconstruction: a meta-analysis of 5182 patients. Am J Sports Med. 2013;41(10):2439–48. https://doi.org/10.1177/0363546513484127.
23. Ellis HB, Matheny LM, Briggs KK, Pennock AT, Steadman JR. Outcomes and revision rate after bone-patellar tendon-bone allograft versus autograft anterior cruciate ligament reconstruction in patients aged 18 years or younger with closed physes. Arthroscopy. 2012;28(12):1819–25. https://doi.org/10.1016/j.arthro.2012.06.016.
24. Kaeding CC, Aros B, Pedroza A, Pifel E, Amendola A, Andrish JT, Dunn WR, Marx RG, McCarty EC, Parker RD, Wright RW, Spindler KP. Allograft versus autograft anterior cruciate ligament reconstruction: predictors of failure from a MOON prospective longitudinal cohort. Sports Health. 2011;3(1):73–81. https://doi.org/10.1177/1941738110386185.
25. Steadman JR, Matheny LM, Hurst JM, Briggs KK. Patient-Centered outcomes and revision rate in patients undergoing ACL reconstruction using bone-patellar tendon-bone autograft compared with bone-patellar tendon-bone allograft: a matched case-control study. Arthroscopy. 2015;31(12):2320–6. https://doi.org/10.1016/j.arthro.2015.06.009.

26. Zeng C, Gao SG, Li H, Yang T, Luo W, Li YS, Lei GH. Autograft versus allograft in anterior cruciate ligament reconstruction: a meta-analysis of randomized controlled trials and systematic review of overlapping systematic reviews. Arthroscopy. 2016;32(1):153–163 e118. https://doi.org/10.1016/j.arthro.2015.07.027.
27. Giedraitis A, Arnoczky SP, Bedi A. Allografts in soft tissue reconstructive procedures: important considerations. Sports Health. 2014;6(3):256–64. https://doi.org/10.1177/1941738113503442.
28. Noyes FR, Barber-Westin SD, Hewett TE. High tibial osteotomy and ligament reconstruction for varus angulated anterior cruciate ligament-deficient knees. Am J Sports Med. 2000;28(3):282–96.
29. Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: results using a quadriceps tendon-patellar bone autograft. Am J Sports Med. 2006;34(4):553–64. https://doi.org/10.1177/0363546505281812.
30. Noyes FR, Barber-Westin SD. Revision anterior cruciate surgery with use of bone-patellar tendon-bone autogenous grafts. J Bone Joint Surg Am. 2001;83-A(8):1131–43.
31. Amis A, Dawkins G. Functional anatomy of the anterior cruciate ligament. Fibre bundle actions related to ligament replacements and injuries. J Bone Joint Surg. 1991;73B(2):260–7.
32. Colombet P, Robinson J, Christel P, Franceschi JP, Djian P, Bellier G, Sbihi A. Morphology of anterior cruciate ligament attachments for anatomic reconstruction: a cadaveric dissection and radiographic study. Arthroscopy. 2006;22(9):984–92.
33. Hefzy MS, Grood ES, Noyes FR. Factors affecting the region of most isometric femoral attachments. Part II: the anterior cruciate ligament. Am J Sports Med. 1989;17(2):208–16.
34. Sidles JA, Larson RV, Garbini JL, Downey DJ, Matsen FA III. Ligament length relationship in the moving knee. J Orthop Res. 1988;6(4):593–610.
35. Gardner EJ, Noyes FR, Jetter AW, Grood ES, Harm SP, Levy MS. Effect of anteromedial and posterolateral ACL bundles on resisting medial and lateral tibiofemoral compartment subluxations: poster P408. In: Paper presented at the annual meeting American Academoy of orthopaedic surgeons. Chicago, IL; 2013.
36. Harm SP, Noyes FR, Jetter AW, Grood ES, Levy MS, Gardner EJ. Anatomic single graft ACL reconstruction restores rotational stability: a novel robotic study in cadaveric knees: paper #362. In: Paper presented at the annual meeting of the American Academy of orthopaedic surgeons. Chicago, IL; 2013.
37. Noyes FR, Jetter AW, Grood ES, Harms SP, Gardner EJ, Levy MS. Anterior cruciate ligament function in providing rotational stability assessed by medial and lateral tibiofemoral compartment translations and subluxations. Am J Sports Med. 2015;43(3):683–92. https://doi.org/10.1177/0363546514561746.
38. Harms SP, Noyes FR, Grood ES, Jetter AW, Huser LE, Levy MS, Gardner EJ. Anatomic single-graft anterior cruciate ligament reconstruction restores rotational stability: a robotic study in cadaveric knees. Am J Sports Med. 2015;31:1981–90.
39. Clancy WGJ, Nelson DA, Reider B, Narechania RG. Anterior cruciate ligament reconstruction using one-third of the patellar ligament, augmented by extra-articular tendon transfers. J Bone Joint Surg. 1982;64A(3):352–9.
40. Piefer JW, Pflugner TR, Hwang MD, Lubowitz JH. Anterior cruciate ligament femoral footprint anatomy: systematic review of the 21st century literature. Arthroscopy. 2012;28(6):872–81. https://doi.org/10.1016/j.arthro.2011.11.026.
41. Noyes FR, Barber SD, Mangine RE. Bone-patellar ligament-bone and fascia lata allografts for reconstruction of the anterior cruciate ligament. J Bone Joint Surg Am. 1990;72(8):1125–36.
42. Noyes FR, Barber SD. The effect of an extra-articular procedure on allograft reconstructions for chronic ruptures of the anterior cruciate ligament. J Bone Joint Surg Am. 1991;73(6):882–92.
43. Noyes FR, Barber SD. The effect of a ligament-augmentation device on allograft reconstructions for chronic ruptures of the anterior cruciate ligament. J Bone Joint Surg Am. 1992;74(7):960–73.
44. Noyes FR, Barber-Westin SD. A comparison of results in acute and chronic anterior cruciate ligament ruptures of arthroscopically assisted autogenous patellar tendon reconstruction. Am J Sports Med. 1997;25(4):460–71.
45. Barber-Westin SD, Noyes FR, Andrews M. A rigorous comparison between the sexes of results and complications after anterior cruciate ligament reconstruction. Am J Sports Med. 1997;25(4):514–26.
46. Noyes FR, Barber-Westin SD. Anterior cruciate ligament reconstruction with autogenous patellar tendon graft in patients with articular cartilage damage. Am J Sports Med. 1997;25(5):626–34.
47. Noyes FR, Mangine RE, Barber S. Early knee motion after open and arthroscopic anterior cruciate ligament reconstruction. Am J Sports Med. 1987;15(2):149–60.
48. Noyes FR, Barber SD, Simon R. High tibial osteotomy and ligament reconstruction in varus angulated, anterior cruciate ligament-deficient knees. A two- to seven-year follow-up study. Am J Sports Med. 1993;21(1):2–12.
49. Barber-Westin SD, Noyes FR. The effect of rehabilitation and return to activity on anterior-posterior knee displacements after anterior cruciate ligament reconstruction. Am J Sports Med. 1993;21(2):264–70.
50. Andrews M, Noyes FR, Barber-Westin SD. Anterior cruciate ligament allograft reconstruction in the skeletally immature athlete. Am J Sports Med. 1994;22(1):48–54.
51. Noyes FR, Barber-Westin SD. The treatment of acute combined ruptures of the anterior cruciate and medial ligaments of the knee. Am J Sports Med. 1995;23(4):380–9.
52. Noyes FR, Barber-Westin SD. Reconstruction of the anterior cruciate ligament with human allograft.

Comparison of early and later results. J Bone Joint Surg Am. 1996;78(4):524–37.
53. Noyes FR, Barber-Westin SD. A comparison of results of arthroscopic-assisted anterior cruciate ligament reconstruction between workers' compensation and noncompensation patients. Arthroscopy. 1997;13(4):474–84.
54. Noyes FR, Barber-Westin SD. Arthroscopic-assisted allograft anterior cruciate ligament reconstruction in patients with symptomatic arthrosis. Arthroscopy. 1997;13(1):24–32.
55. Barber-Westin SD, Noyes FR, Heckmann TP, Shaffer BL. The effect of exercise and rehabilitation on anterior-posterior knee displacements after anterior cruciate ligament autograft reconstruction. Am J Sports Med. 1999;27(1):84–93.
56. Noyes FR, Barber-Westin SD. Reconstruction of the anterior and posterior cruciate ligaments after knee dislocation. Use of early protected postoperative motion to decrease arthrofibrosis. Am J Sports Med. 1997;25(6):769–78.
57. Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscus tears extending into the avascular zone with or without anterior cruciate ligament reconstruction in patients 40 years of age and older. Arthroscopy. 2000;16(8):822–9. https://doi.org/10.1053/jars.2000.19434.
58. Ahn JH, Kim JG, Wang JH, Jung CH, Lim HC. Long-term results of anterior cruciate ligament reconstruction using bone-patellar tendon-bone: an analysis of the factors affecting the development of osteoarthritis. Arthroscopy. 2012;28(8):1114–23. https://doi.org/10.1016/j.arthro.2011.12.019.
59. Barenius B, Ponzer S, Shalabi A, Bujak R, Norlen L, Eriksson K. Increased risk of osteoarthritis after anterior cruciate ligament reconstruction: a 14-year follow-up study of a randomized controlled trial. Am J Sports Med. 2014;42(5):1049–57. https://doi.org/10.1177/0363546514526139.
60. Keays SL, Newcombe PA, Bullock-Saxton JE, Bullock MI, Keays AC. Factors involved in the development of osteoarthritis after anterior cruciate ligament surgery. Am J Sports Med. 2010;38(3):455–63. https://doi.org/10.1177/0363546509350914.
61. Li RT, Lorenz S, Xu Y, Harner CD, Fu FH, Irrgang JJ. Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. Am J Sports Med. 2011;39(12):2595–603. https://doi.org/10.1177/0363546511424720.
62. Nakata K, Shino K, Horibe S, Tanaka Y, Toritsuka Y, Nakamura N, Koyanagi M, Yoshikawa H. Arthroscopic anterior cruciate ligament reconstruction using fresh-frozen bone plug-free allogeneic tendons: 10-year follow-up. Arthroscopy. 2008;24(3):285–91.
63. Salmon LJ, Russell VJ, Refshauge K, Kader D, Connolly C, Linklater J, Pinczewski LA. Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. Am J Sports Med. 2006;34(5):721–32.
64. Shelbourne KD, Gray T. Minimum 10-year results after anterior cruciate ligament reconstruction: how the loss of normal knee motion compounds other factors related to the development of osteoarthritis after surgery. Am J Sports Med. 2009;37(3):471–80. https://doi.org/10.1177/0363546508326709.
65. Noyes FR, Barber-Westin SD. Treatment of meniscus tears during anterior cruciate ligament reconstruction. Arthroscopy. 2012;28(1):123–30. https://doi.org/10.1016/j.arthro.2011.08.292.
66. Noyes FR, Barber-Westin SD. Meniscus tears: diagnosis, repair techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 677–718.
67. Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscal tears extending into the avascular zone in patients younger than twenty years of age. Am J Sports Med. 2002;30(4):589–600.
68. Rubman MH, Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscal tears that extend into the avascular zone. A review of 198 single and complex tears. Am J Sports Med. 1998;26(1):87–95.
69. Heckmann TP, Noyes FR, Barber-Westin SD. Rehabilitation of meniscus repair and transplantation procedures. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 760–71.
70. Buseck MS, Noyes FR. Arthroscopic evaluation of meniscal repairs after anterior cruciate ligament reconstruction and immediate motion. Am J Sports Med. 1991;19(5):489–94.
71. Noyes FR, Barber-Westin SD. Management of special problems associated with knee menisci: repair of complex and avascular tears and meniscus transplantation. In: Egol KA, editor. Instructional course lectures, vol. 60. Rosemont: AAOS; 2010.
72. Barber-Westin SD, Noyes FR. Clinical healing rates of meniscus repairs of tears in the central-third (red-white) zone. Arthroscopy. 2014;30(1):134–46. https://doi.org/10.1016/j.arthro.2013.10.003.

11 Early Postoperative Rehabilitation to Avoid Complications and Prepare for Return to Sport Training

Frank R. Noyes and Sue Barber-Westin

11.1 Introduction

Considerable advances have been made in the treatment of complete anterior cruciate ligament (ACL) ruptures and reconstruction methods. These include the appropriate selection of patient candidates and criteria that should be achieved before surgery including resolving limitations of knee motion, muscle atrophy, gait abnormalities, pain, and joint effusion (see Chap. 8) [1–8]. The majority of patients who undergo ACL reconstruction are athletes under 25 years of age who are frequently involved in high school, collegiate, or league athletics. The major goals are to stabilize the knee to prevent future reinjuries and allow a safe return to sport (RTS). Although these goals are successfully achieved in many patients, reinjury rates (to either the ACL-reconstructed or contralateral knee) range from 3 to 22% [9–25]. Factors that are frequently cited as associated with reinjuries include younger age, return to high-impact sports that involve cutting and pivoting, and use of an allograft or hamstring autograft. Allowing athletes to RTS without a comprehensive objective assessment of muscle strength, neuromuscular function, ACL graft function, and range of knee motion may also be a source of high reinjury rates. Failure to restore complex neuromuscular function required for landing, pivoting, and cutting in both limbs could place both the ACL-reconstructed and contralateral knee at increased risk. Other factors that may result in failure of ACL reconstructions include surgical errors (use of low-strength grafts, inadequate fixation, graft impingement in the notch, or excessive or insufficient graft tensioning at surgery); failure of graft integration, tendon-to-bone healing, or remodeling; uncorrected lateral, posterolateral, or medial ligament deficiency; and postoperative infection.

We believe that a comprehensive rehabilitation program following ACL reconstruction is crucial to enable patients to RTS as safely as possible. After surgery, the main goals of rehabilitation are to prevent complications such as arthrofibrosis and reinjury and eventually achieve normal to nearly normal knee function. There are many factors that may impact both the initial and long-term recovery after ACL reconstruction (Table 11.1) [3, 26]. Patients must regain full knee motion, normal patellar mobility, normal gait mechanics, and adequate lower extremity muscle strength, coordination, proprioception, and neuromuscular function for their desired activities. The exercise program should not produce undue forces on the healing ACL graft and patellofemoral or tibiofemoral compartments or

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_11

Table 11.1 Factors affecting recovery after anterior cruciate ligament reconstruction

1. Resolution of limitations in knee motion, muscle atrophy, gait abnormalities, pain, and knee joint effusion *before* surgery
2. The amount of time between injury and surgery
3. Reinjuries before surgery
4. Meniscectomy before or with ACL reconstruction
5. The preinjury sports activity level
6. Patient age
7. ACL graft selection, harvest, placement, fixation, healing, and remodeling
8. Initial patient response to surgery including pain, effusion, and muscle inhibition
9. Psychological factors before surgery and during postoperative recovery such as motivation, beliefs, compliance, self-efficacy, locus of control, and fear of reinjury
10. The condition of the articular cartilage
11. The presence and severity of bone bruising
12. Concomitant major operative procedures: meniscus repairs or transplants, other ligament reconstructions, patellofemoral realignment procedures, and articular cartilage restorative procedures
13. Lingering postoperative deficits in muscle strength and neuromuscular function
14. Patellofemoral pain or tendinitis
15. Restoration of normal knee stability
16. Previous ACL reconstruction that failed
17. Premature return to strenuous activities before restoration of normal muscle strength and neuromuscular control and both limbs has been achieved

precipitate chronic joint effusions. Because of the published documentation of neuromuscular deficits in both the reconstructed and contralateral limbs postoperatively [26], failure to address and fully rehabilitate both knees may be a factor for high postoperative reinjury rates.

At our center, the postoperative rehabilitation program takes into account the patient's sports and occupational goals; the condition of the articular surfaces, menisci, and other knee ligaments; concomitant operative procedures performed with the ACL reconstruction; the type of graft used; postoperative healing and response to surgery; and biologic principles of graft healing and remodeling. The rehabilitation program incorporates open and closed kinetic chain activities for muscle strengthening and cardiovascular conditioning along with neuromuscular training techniques.

Patients who express the desire to resume strenuous sports activities early after surgery are warned of the risk of a reinjury to the ACL-reconstructed knee or a new injury to the contralateral knee. At our center, advanced neuromuscular training (Sportsmetrics) is recommended in all athletes before returning to sports involving cutting, pivoting, and repetitive jumping. In addition, athletes must pass a series of tests described in Chaps. 20 and 21 before they are released to unrestricted athletics.

The early return to athletics is not allowed in patients in whom an allograft was used or those who underwent concomitant major operative procedures such as a complex meniscal repair, other ligament reconstructions, patellofemoral realignment, articular cartilage restorative procedure, or osteotomy. Strenuous athletics are not recommended in patients undergoing revision ACL reconstruction or those in whom magnetic resonance imaging or arthroscopic evidence of major bone bruising or articular cartilage damage exists. These patients are entered into a postoperative protocol that incorporates delays in return of full weight-bearing, initiation of certain strengthening and conditioning exercises, beginning running and agility drills, and return to full sports activities [27].

This chapter provides our recommendations for exercises and goals for the initial phases of rehabilitation based on over three decades of experience and multiple clinical studies [28–33]. Chapter 8 details the preoperative rehabilitation program required to assist the patient recover from the injury; reestablish full knee motion, muscle strength, and neuromuscular control; and educate the patient and family regarding the surgery and postoperative program. Chapter 14 details advanced neuromuscular training concepts (including Sportsmetrics) that are incorporated in later phases of rehabilitation as the patient begins sports-specific rehabilitation. In addition, recommendations for objective, neurocognitive, and psychological testing are discussed throughout this textbook.

Critical Points

- Major goals are to stabilize the knee to prevent future reinjuries and allow a safe return to previous sports levels.
- Following surgery, reinjury rates range from 3 to 22%.
  - Multiple reasons for reinjuries, ACL graft failure
- Successful ACL rehab program:
  - Regain full range of motion, gait
  - Adequate strength for activity level
  - Normal bilateral proprioception, neuromuscular function
- Rehab program is designed based on:
  - Patient's sports, occupational goals
  - Condition of articular cartilage surfaces, menisci, other knee ligaments
  - Concomitant operative procedures
  - Type of graft used
  - Postoperative healing, graft remodeling

11.2 Clinical Concepts

11.2.1 Control Knee Joint Effusion

A knee joint effusion may precipitate reflex inhibition of the quadriceps, leading to weakness and atrophy. Several investigators have shown that quadriceps muscle inhibition occurs following experimentally induced knee joint effusions and produces alterations in normal function during walking, jogging, and landing from a jump [34–37]. Knee joint effusions must be avoided or treated immediately to lessen these deleterious impacts on quadriceps function. Joint aspiration, cryotherapy, transcutaneous electrical nerve stimulation, and compression are effective therapeutic measures [38, 39]. Prudent, short-term use of non-steroidal anti-inflammatory medications may also be required.

11.2.2 Immediate Knee Motion and Early Weight-Bearing

The scientific basis supporting immediate range of motion (ROM) exercises after ACL reconstruction is well established [5, 33, 40–44]. The use of an immediate postoperative knee motion program (in the range of 0–90°) after ACL reconstruction was initiated in our center in 1981 [45]. Early knee joint motion decreases pain and postoperative joint effusions, aids in the prevention of scar tissue formation and arthrofibrosis, decreases muscle atrophy, maintains articular cartilage nutrition, and benefits the healing ACL graft [6, 46, 47]. Studies conducted many years ago demonstrated the detrimental effects of immobilization, including permanent limitation of knee motion, prolonged muscle atrophy, patella infera, and articular cartilage deterioration [46, 48–51]. Failure to achieve full knee motion may cause abnormal joint arthrokinematics, increased contact pressures in the patellofemoral and/or tibiofemoral joints, patellofemoral osteoarthritis, and a poor outcome [52–55]. Shelbourne et al. [56] reported the effects of lacking normal extension or flexion at the time of discharge from physical therapy in 423 patients followed a mean of 22.5 ± 2.1 years after ACL reconstruction. Lacking normal knee extension at discharge increased the odds of developing moderate or severe osteoarthritis by 1.46, whereas lacking normal extension at follow-up increased the odds by 3.36 ($P < 0.0001$). Similar results were reported for loss of normal flexion.

Although many authors have recommended immediate partial or full weight-bearing after ACL reconstruction, few studies have examined its potential effect on both short- and long-term recovery [57, 58], especially in knees with noteworthy articular cartilage damage or those in which major concomitant operative procedures were required. In addition, gait abnormalities may ensue from immediate full weight-bearing due to pain, knee joint effusion, and muscle weakness. It does appear from the literature [59–62] and our experience [28] that immediate partial weight-bearing is safe and not deleterious to the healing ACL graft.

11.2.3 Electrical Muscle Stimulation and Biofeedback

Neuromuscular electrical muscle stimulation (EMS) and biofeedback have been recommended early after ACL reconstruction to aid in the initial recovery of quadriceps activation [27, 38, 63–65]. Multiple studies have demonstrated that EMS combined with active exercise is more effective than active exercise alone in recovery of quadriceps strength and normal gait mechanics [63, 64, 66–68]. Wright et al. [69] concluded from a systematic review that high-intensity EMS may help achieve improved quadriceps strength after ACL reconstruction. Imoto et al. [70] concluded from their review that EMS added to conventional exercises may be effective in improving muscle strength and recovery 2 months after surgery.

Biofeedback therapy has been suggested as a useful therapeutic technique in overcoming muscle inhibition early postoperatively [38]. This therapy helps patients develop and increase their voluntary control over muscle contractions [71–73]. However, no high-level studies have been conducted to ascertain the effectiveness of biofeedback following ACL reconstruction in regard to increases in muscle strength and/or reduced quadriceps atrophy.

11.2.4 Muscle Loss After ACL Reconstruction

Lower extremity muscle atrophy and weakness after ACL reconstruction represent a difficult and unresolved problem [74–78]. Investigators have reported postoperative strength deficits ranging from 5 to 40% for the quadriceps and from 9 to 27% for the hamstrings [78–85]. Problems with muscle atrophy appear to occur regardless of the type of graft used to reconstruct the ACL and frequently occur bilaterally [38]. Unresolved postoperative muscle strength deficits may be associated with knee osteoarthritis that is present either at baseline or years after surgery [86–90]. The factors related to the loss of muscle size and strength after ACL reconstruction remain unclear (Table 11.2). Regardless of the cause of muscle atrophy and weakness, it is paramount that the rehabilitation program corrects the deficits in a controlled, effective, and safe manner. There are several principles the therapist must use to achieve this goal, which change as the patient progresses through the program.

Table 11.2 Proposed causes of quadriceps muscle strength deficits after ACL reconstruction [26]

1. Selective atrophy of type 1 fibers [91]
2. A reduction in muscle fiber size [92]
3. Hypertrophy of fast-twitch muscle fibers [93, 94]
4. Nonoptimal activation of muscles during voluntary contractions [95]
5. Loss of native ACL mechanoreceptors that result in abnormal (decreased) gamma loop function [96–103]
6. Arthrogenic muscle inhibition: inhibition of muscle tissue from joint effusion and soft tissue damage leads to altered afferent output from knee joint and muscle atrophy [38, 77, 104, 105]
7. Peripheral changes in muscle-tendon units of the quadriceps muscle, including chronic atrophy, changes in the compliance of the series elastic components of the muscle-tendon units, and alterations in structure and fiber type [106]
8. Elevated levels of atrophy-inducing signaling cytokines such as myostatin and TFG-β [107]
9. Alterations in neural pathways [108]
10. A combination of the above

11.2.5 Regaining Strength: Patellofemoral Joint Protection

It is critical as the clinician progresses the patient through both the early and later stages of rehabilitation after ACL reconstruction to avoid placing high forces on the patellofemoral joint. Patients who develop patellofemoral symptoms must be carefully followed and the rehabilitation program altered as required to avoid activities that place high forces on the patella. Investigators have estimated that the loads on the patellofemoral joint range from 3 times body weight (BW) with stair climbing to 7 times BW with squatting and up to 20 times BW with jumping [109, 110]. Escamilla et al. [111] measured patellofemoral compressive forces during a wall squat closed kinetic chain (CKC) exercise in healthy subjects. The forces ranged from approximately 75 to 1400 N between 0 and 50° of knee flexion and then rose to approximately 2100–3650 between 60 and 90° of knee flexion. This compares to compressive forces incurred on the patellofemoral joint during walking of approximately 900 N. Steinkamp et al. [112] calculated patellofemoral joint reaction forces in normal subjects during a CKC leg press exercise and an open kinetic chain (OKC) leg extension exercise. Reaction forces were significantly greater ($P < 0.001$) at 0° and 30° in the OKC leg extension exercise than during the leg press exercise. The opposite was true at the high knee flexion angles, for which forces were significantly greater in the leg press exercise.

Anterior or patellofemoral knee pain that develops after ACL reconstruction is a difficult complication [113, 114], and it is essential that the therapist understands the impact that exercises have on the patellofemoral joint. We recommend avoidance of the leg extension machine in the range of 30° to 0° of knee flexion and exercises that involve high knee flexion angles such as deep squatting, kneeling (past 50°), and extensive stair climbing in the first 3 months after surgery. In low ranges of knee motion, CKC exercises are recommended because of the desirable patellar positioning and decrease in potential joint irritation [111, 115–118]. Some examples include mini-squats (to 45° of knee flexion), wall sits (to 50° of flexion), lateral step-ups, and forward step-ups. One study compared patellofemoral reaction forces and stresses during forward step-up, lateral step-up, and forward step-down exercises [119]. The step height for each subject was adjusted to allow for a knee flexion angle of 45°. When averaged across concentric and eccentric phases, peak patellofemoral stress and peak patellofemoral reaction forces were significantly greater during the forward step-down compared with the other exercises ($P < 0.01$ and $P < 0.05$, respectively). Forward step-down exercises should therefore be avoided in patients with patellofemoral pain. The leg press machine is recommended because it places minimal stress on the patellofemoral joint in the functional ROM [112]; however, high knee flexion angles should be avoided.

11.2.6 Open and Closed Kinetic Chain Exercises: Which Are Safe Early Postoperatively?

The process of ACL graft maturation and healing is assumed to be influenced by strains and forces applied to the lower limb during weight-bearing and exercises. While a general consensus exists that some strain is necessary to promote the process of ligamentization [120], the amount of load that is safe versus the amount that may produce graft elongation remains questionable. Several investigations have attempted to measure force and strain incurred on the ACL during common OKC and CKC exercises used in rehabilitation.

Direct in vivo measurement of ACL strain incurred during activities has been conducted by several investigators [121–128]. Beynnon and colleagues performed a series of studies in which a Hall effect transducer was arthroscopically implanted into the anteromedial fibers of the normal ACL in volunteers undergoing surgical procedures under local anesthesia [122, 123, 125, 127, 129]. Patients performed several OKC and CKC exercises at different knee flexion angles. The mean peak ACL strains reported in these studies are shown in Table 11.3 [120], and it is important to note that these investigators emphasized that the limits of ACL strain that are safe and not deleterious to healing ACL grafts remain unknown.

Escamilla et al. [130] summarized data from multiple experimental biomechanical models and in vivo measurements of ACL strain and tensile forces. The authors concluded that for both weight-bearing and non-weight-bearing exercises, greater ACL loading occurs at lower knee flexion angles, with peak loading occurring between 10 and 30° of knee flexion. ACL loading then progressively decreases from 30 to 60°, with no ACL loading occurring beyond 60° of flexion. In addition, the magnitude of ACL loading between 10 and 50° of flexion is greater during non-weight-bearing exercises, such as seated knee extension, than during weight-bearing exercises. Weight-bearing exercises also recruit important muscles at both the hip and knee.

CKC exercises such as double-leg squatting from 0 to 45° of knee flexion are safe early after ACL reconstruction [131, 132]. This may be progressed to single-leg squatting as the patient achieves full pain-free weight-bearing. It is important to realize that technique affects both muscle recruitment and ACL loading. For instance, a forward trunk position of 30–40°

Table 11.3 Rank comparison of mean peak ACL strain values measured in vivo in healthy subjects [120]

Exercise	Open kinetic chain (OKC) or closed kinetic chain (CKC)	Peak ACL strain (%)
Isometric quadriceps contraction at 15° (30 Nm extension torque)	OKC	4.4
Squat with Sport Cord	CKC	4.0
Lachman test at 30° (150 N anterior shear load)	NA	3.7
Squat, no resistance	CKC	3.6
Isometric gastrocnemius contraction at 15° (15 Nm plantar flexion torque)	OKC	3.5
Active flexion and extension, no resistance	OKC	2.8
Co-contraction quadriceps and hamstrings at 15°	OKC	2.8
Isometric gastrocnemius contraction at 5° (15 Nm plantar flexion torque)	OKC	2.8
One-leg sit to stand exercise	CKC	2.8
Isometric quadriceps contraction at 30° (30 Nm extension torque)	OKC	2.7
Stair climbing	CKC	2.7
Step-up and step-down	CKC	2.5
Weight-bearing at 20°	NA	2.1
Leg press at 20° (40% body weight)	CKC	2.1
Anterior drawer test at 90° (150 N anterior shear load)	NA	1.8
Lunge	CKC	1.8
Stationary bicycling	CKC	1.7
Isometric hamstrings contraction at 15° (10 Nm flexion torque)	OKC	<1
Co-contraction quadriceps and hamstrings at 30°	OKC	<1
Isometric gastrocnemius contraction at 30° (15 Nm plantar flexion torque)	OKC	<1
Passive flexion and extension	OKC	<1
Isometric quadriceps contraction at 60° and 90° (30 Nm extension torque)	OKC	0
Isometric gastrocnemius contraction at 45° (15 Nm plantar flexion torque)	OKC	0
Co-contraction quadriceps and hamstrings at 60° and 90°	OKC	0
Isometric hamstrings contraction at 30°, 60°, and 90° (10 Nm flexion torque)	OKC	0

during a squat will recruit greater hamstrings activity and lessen ACL loading, while an erect trunk position results in greater quadriceps activation and increased ACL loading [133, 134]. Forward and side lunges in the range of 0–45° of knee flexion are also safe and effective due to the relatively high hamstrings activation. The leg press machine produces no ACL tensile forces and is also a preferred CKC exercise. The stationary bicycle is also recommended in the initial recovery phase after surgery.

Studies have reported that the early incorporation of certain OKC exercises early postoperatively does not adversely affect anterior tibial translation compared with the later initiation of these exercises [43, 59, 60, 135, 136]. These exercises include:

(1) Leg extensions in the range of 45–90° [59, 60, 136–138]
(2) Short arc quadriceps sets from 0 to 30°[136]
(3) Quadriceps isometrics at 0° [60, 136, 139]
(4) Quadriceps-hamstrings co-contraction isometrics at 0° [43, 60, 136, 139]

Muscle EMG activation patterns that occur during OKC and CKC exercises have been measured in several studies in uninjured subjects [131, 140–149]. Notable findings included:

(1) High and balanced levels of quadriceps activation occurred during CKC single-leg squat, step-ups, and leg press tasks [131, 145, 146].
(2) The single-leg wall squat had the highest muscle efficiency compared with other single-leg CKC exercises [142].
(3) Trunk position affected muscle activity patterns during the forward lunge exercise [141].
(4) Balanced quadriceps-hamstrings co-contractions occurred during the single-leg dead lift, single-leg transverse (rotational) hop, single-leg lateral hop, and lateral band walking exercises (Table 11.4) [140].

Table 11.4 Normalized percent muscle contraction averages for quadriceps and hamstrings and coactivation ratios in healthy recreationally active college students[a] [140]

Exercise	Quadriceps MVIC	Hamstrings MVIC	Q:H coactivation ratio
Single-leg dead lift	65.71 ± 29.40	24.15 ± 8.51[b,c]	2.87 ± 1.77[d]
Single-leg transverse hop	48.46 ± 40.04	16.47 ± 10.29	3.77 ± 3.51[d]
Single-leg lateral hop	67.84 ± 42.18	17.97 ± 8.79	3.83 ± 3.51[d]
Lateral band walk	45.27 ± 19.01	10.69 ± 6.05	3.64 ± 1.57[d]
Single-leg forward hop	75.87 ± 58.77	14.66 ± 7.58	5.26 ± 4.43
Single-leg squat	113.27 ± 38.49[e]	22.24 ± 8.42[c]	5.52 ± 2.89
Transverse lunge	123.73 ± 51.06[e]	20.99 ± 9.09[c]	7.78 ± 5.51
Lateral lunge	141.42 ± 55.07[e]	15.08 ± 7.37	9.30 ± 5.53[f]
Forward lunge	128.42 + 57.32[e]	15.20 ± 7.98	9.70 ± 5.90[f]

MVIC maximum voluntary isometric contraction, *Q:H* quadriceps-to-hamstrings
[a] Values shown are mean ± SD
[b] Exercise greater hamstrings activation than lateral band walk, forward hop, lateral lunge, and forward lunge ($P < 0.01$)
[c] Exercise greater hamstrings activation than lateral band walk ($P < 0.001$)
[d] Exercise different from all three lunge exercises ($P < 0.01$)
[e] Exercise greater quadriceps activation than lateral band walk, single-leg dead lift, and all hopping exercises ($P < 0.01$)
[f] Exercise different from all other exercises ($P < 0.01$)

Our protocol for muscle-strengthening exercises for the first 26 postoperative weeks after ACL reconstruction is shown in Table 11.5 [27].

11.2.7 Other Muscle Training Options

Eccentric training has been proposed to enhance increases in muscle cross-sectional area (CSA), volume, and strength after ACL reconstruction [151–157]. This type of training is believed by some to be superior to concentric training owing to its potential to overload the muscle and produce greater increases in muscle size and strength. Gerber et al. [154] used a progressive, gradual eccentric training protocol from 3 to 15 weeks after ACL reconstruction in 16 patients. These investigators reported that patients who completed this program had a twofold greater increase in quadriceps CSA, volume, and strength compared with patients who followed a standard rehabilitation program only. There were no significant differences between groups in the improvement in volume and CSA of the hamstring muscles. Brasileiro et al. [156] reported significant improvement in isokinetic peak torque and quadriceps CSA following 6 weeks of eccentric training in nine ACL-reconstructed subjects. The training was conducted on an isokinetic dynamometer 9–10 months postoperatively.

In a cohort of male soldiers who underwent ACL hamstring reconstruction, Papandreou et al. [157] reported significant differences in quadriceps strength between patients who followed a program of 8 weeks of eccentric training (done during postoperative weeks 1–8) combined with standard rehabilitation and patients who completed standard rehabilitation only. Both the reconstructed and contralateral limbs were trained in the two experimental groups, one which trained 3 days a week and one which trained 5 days a week. Although all groups reported noteworthy decreases in isometric quadriceps strength, the experimental groups had significantly lower losses of strength (Table 11.6). There are concerns with high-force eccentric training after ACL reconstruction, including the potential for inducing damage to the muscle and healing graft. Further high-level research is required to determine the efficacy of this type of training.

Recently, studies have begun to explore the use of blood flow-restricted training (BFRT) with low resistance loads (such as 30% 1 repetition maximum) in individuals who cannot tolerate high-load resistance training (Fig. 11.1) [158]. Three studies have assessed the effect of BFRT initiated early after ACL reconstruction (which varied from the first postoperative day to the second postoperative week) [159–161] on quadriceps CSA. The BFRT groups had less quadriceps atrophy early postoperatively in two

Table 11.5 Muscle-strengthening exercises [150]

Time postop, frequency, duration	Quadriceps isometrics (active)	Straight leg raises	Knee extension (active-assisted, 90–30°)	Toe raises, heel raises	Wall sits (to fatigue)	Mini-squats	Hamstring curls (active, 0–90°)	Multi-hip	Leg press (80–10°)
1–2 weeks, 3 times per day, 15 min	1 set × 10 reps every hour patient is awake	All four planes 3 sets × 10 reps	3 sets × 10 reps			0–45°, 50% weight-bearing: 3 sets × 20 reps	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps
3–4 weeks, 2–3 times per day, 20 min	Multi-angle: 90°, 60°, 30° 1 set × 10 reps each angle	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps	5 reps	3 sets × 20 reps	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps
5–6 weeks, 1–2 times per day, 20 min	Multi-angle: 30°, 60°, 90° 3 sets × 10 reps each angle	With ankle weight (≤10% of body weight): 3 sets × 10 reps With resistance band: 3 sets × 10 reps	With resistance: 3 sets × 10 reps	3 sets × 10 reps	5 reps	3 sets × 20 reps	With resistance: 3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps
7–8 weeks, 1–2 times per day, 20 min		With resistance band: 3 sets × 30 reps	With resistance: 3 sets × 10 reps	3 sets × 10 reps	5 reps	3 sets × 20 reps	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps
9–12 weeks, 1 time a day, 20 min		With resistance band: 3 sets × 30 reps	With resistance: 3 sets × 10 reps	3 sets × 10 reps	5 reps	3 sets × 20 reps	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps
13–26 weeks, 1 time a day 20–30 min, 3 times per week machines		With resistance band, high speed, 3 sets × 30 reps	With resistance: 3 sets × 10 reps				3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps

Reps repetitions

Table 11.6 Effect of eccentric training: quadriceps isometric strength changes 8 weeks after ACL reconstruction [157]

Group	ACL-reconstructed limb		Contralateral limb (Nm)		Mean difference reconstructed-contralateral (%)	
	% decrease pre-postop	Nm 8 weeks postop	% increase pre-postop	Nm 8 weeks postop	Preop	8 weeks postop
Group A (3 days per week; $n = 14$)	−16.25 ± 24.70	344.80 ± 135.23	22.70 ± 20.60	458.75 ± 87.33	12.17 ± 9.30[a]	27.95 ± 24.20[a]
Group B (5 days per week; $n = 14$)	−6.30 ± 26.01	295.50 ± 84.80	18.00 ± 17.60	394.00 ± 91.20	17.22 ± 15.45[a]	29.82 ± 21.05[a]
Control ($n = 14$)	−37.83 ± 16.90	225.30 ± 122.30	14.08 ± 16.20	487.95 ± 108.33	24.32 ± 17.95	53.00 ± 24.20

[a]Significantly less than the control group ($P < 0.05$)

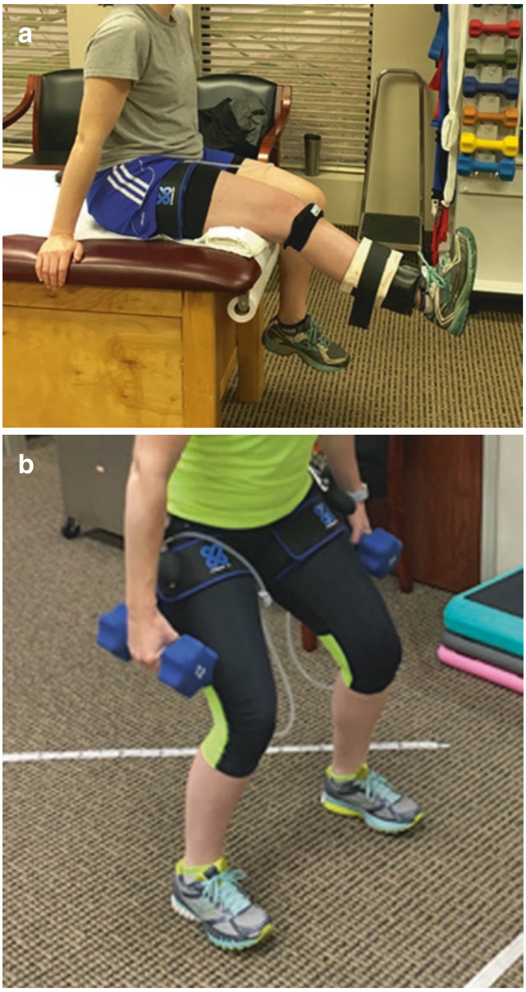


Fig. 11.1 Examples of blood flow-restricted exercise training that may be done non-weight-bearing, such as during knee extension (**a**), or weight-bearing, such as during partial squatting (**b**) (Reprinted from Barber-Westin and Noyes [158])

of the studies [159, 160]. One study conducted training from weeks 2 to 16 postoperatively and reported a significant effect of training for the quadriceps involved limb-uninvolved limb ratio at 60°/s, 180°/s, and isometric mode compared with a control group [159]. The use of short-duration vascular occlusion and low-load resistance exercises appears safe and not deleterious after knee surgery or in arthritic knees. This treatment option requires further investigation to refine protocols related to cuff pressure and exercise dosage and duration.

11.2.8 Early Restoration of Neuromuscular Function

Restoration of normal neuromuscular function after ACL reconstruction is paramount for the eventual implementation of sports-specific exercises and release to full activities [27, 162]. Knee joint proprioception is considered by many to be a crucial element of neuromuscular function and its recovery essential for a successful outcome [52, 163]. Proprioception is altered after ACL injury from damage incurred to the joint mechanoreceptors and muscle afferents and may be further impaired with a concurrent meniscus tear [164, 165]. Dynamic postural control or stability is another important neuromuscular factor that must be restored after ACL reconstruction. Balance requires constant adjustment to the body's muscular activity and positioning and is influenced by the integration of sensorimotor information into the central nervous system and the resultant motor response. Impairment in postural stability is believed to be related, in part, to deficiencies in proprioception [166, 167].

Howells and associates [168] reviewed ten studies of ACL reconstruction and concluded that subjects appeared to have impaired postural control, especially in dynamic tasks that were relevant to sports activities. Subsequently, other studies demonstrated impairments in dynamic postural stability in athletes [169–172]. A general consensus exists that the ACL postoperative rehabilitation program should include exercises believed to improve proprioception and postural stability as soon as possible after surgery and gradually progress in difficulty. Our protocol for balance and proprioception exercises to perform for the first 26 postoperative weeks after ACL reconstruction is shown in Table 11.7.

Critical Points

- Control or treat knee joint effusions immediately.
- Immediate knee motion safe and effective.
- Early partial weight-bearing not deleterious to healing graft.

Table 11.7 Balance and proprioception exercises [150]

Time postop	Frequency, duration	Weight shifting	Balance board	Cup walking	Single-leg stance	Front and lateral step-ups	Resistance band walking	Plyoback ball toss	Perturbation training
1–2 weeks	3 times per day, 5 min	Side-side and forward-backward 5 sets × 10 reps							
3–4 weeks	3 times per day, 5 min	Side-side and forward-backward 5 sets × 10 reps	Double leg	Perform	Level surface 5 reps				
5–6 weeks	3 times per day, 5 min		Double leg		Level surface	2–4″ block			
7–8 weeks	3 times per day, 5 min		Double leg		Stable vs. unstable platform	4–6″ block	Start	Start	Start
9–12 weeks	3 times per day, 5 min		Double leg		Unstable platform	6–8″ block	Continue	Continue	Continue
13–26 weeks	3 times per day, 5 min		Single leg		Unstable platform, add secondary activity				

- Muscle loss postoperatively unresolved problem, multiple potential causes.
- Understanding forces on patellofemoral joint important to select appropriate exercises:
  - Avoid leg extension machine 30–0°.
  - Avoid high knee flexion exercises and extensive stair climbing.
  - Closed kinetic chain exercises begun first postoperative week.
- Understanding forces on ACL also important to select appropriate exercises:
  - Safe closed kinetic chain exercises: double-leg squatting 0–45° with forward trunk lean, forward and side lunges 0–45°, leg press, and stationary bicycle
  - Safe open kinetic chain exercises: leg extensions 45–90°, short arc quadriceps sets 0–30°, quadriceps isometrics 0°, and quadriceps-hamstrings co-contraction isometrics 0°
- Eccentric muscle training and blood flow-restricted training potentially effective, require further research.
- Begin proprioceptive and postural control exercises first week postoperatively.

11.3 Recognition of Major Complications

The first few postoperative weeks after ACL reconstruction is the time period to recognize and treat early postoperative problems such as infection, deep venous thrombosis (DVT), arthrofibrosis, patellar tendon or patellofemoral pain, the onset of a pain syndrome, or early graft stretching.

For the first postoperative week, patients should take their oral temperature during the day and at night, and the surgeon should be notified immediately if the patient maintains a low-grade temperature, if the temperature reaches 101 °F, or if the patient experiences persistent joint pain, redness, warmth, and increased swelling. The wound should be inspected weekly by the medical team for redness, swelling, or any other signs of infection. Knee joint aspiration and fluid analysis are done for joint hematoma or if effusion reaches approximately 50 mL. Other rules to prevent and treat knee joint infection have been discussed in detail elsewhere [30].

The protocol for prevention of DVT includes 1 aspirin a day for 10 days and use of a bulky com-

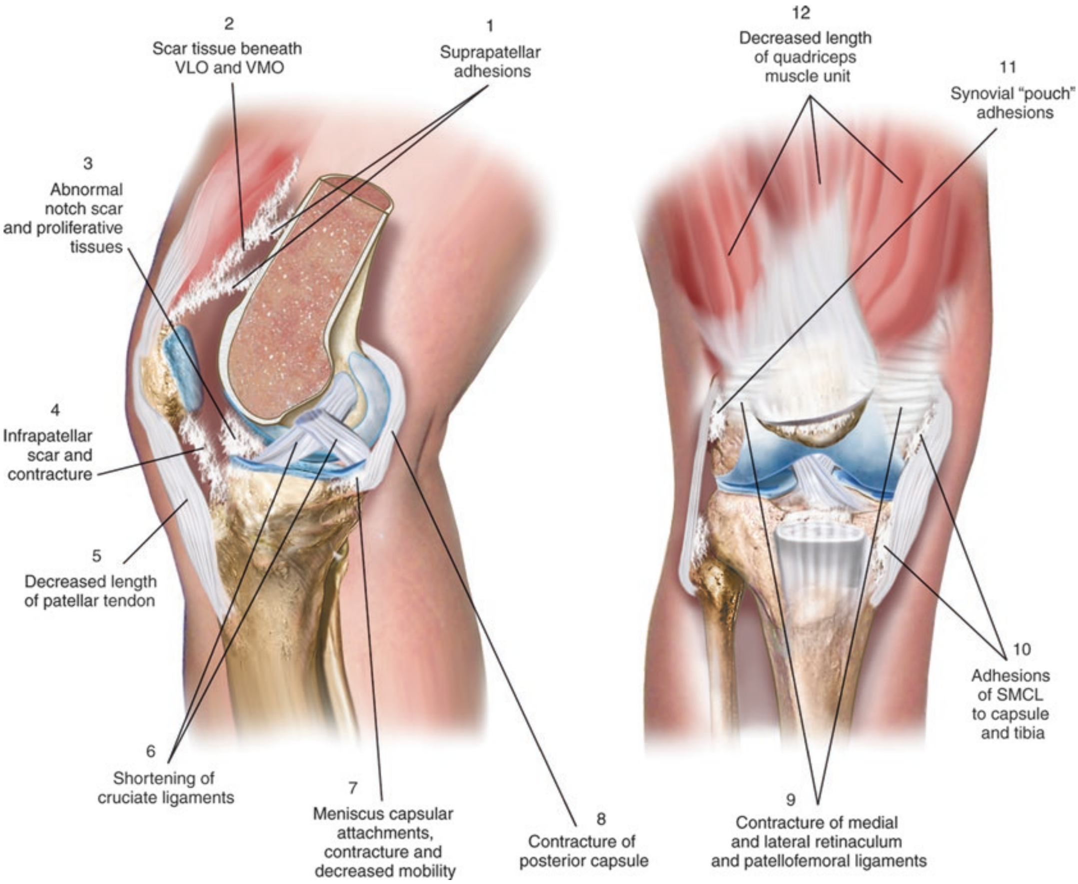


Fig. 11.2 Multiple areas of soft tissue contracture, adhesions, and scar tissue formation with knee arthrofibrosis. *SMCL* superficial medial collateral ligament, *VLO* vastus lateralis oblique, *VMO* vastus medialis oblique (Reprinted from Noyes and Barber-Westin [183])

pression dressing for 24–48 h which is then converted to compression stockings with an additional Ace bandage if necessary. Ambulation (with crutch support) is allowed 6–8 times a day for short periods of time, ankle pumping is encouraged for 5 min every hour that the patient is awake, and the lower limb is closely observed by the therapist and surgeon. Non-steroidal anti-inflammatories are used for at least 5 days postoperatively. Doppler ultrasound should be performed if any suspicion of DVT is noted, including abnormal calf tenderness, a positive Homans sign, or increased lower extremity edema.

Loss of a normal range of knee motion after ACL reconstruction is a potentially devastating complication. There are many potential reasons for this problem, including an impinged or improperly placed ACL graft [173–178], a cyclops lesion [179], improper graft tensioning that constrains normal knee joint motion [180, 181], and graft fixation at ≥30° of extension [182]. Contracture of the posterior capsular structures may limit knee extension. If not resolved early, these problems may result in the development of arthrofibrosis that greatly complicates the course of treatment. Proliferative scar tissue or fibrous adhesions may form within the joint, which can result in either localized or diffuse involvement of all of the compartments of the knee and the extra-articular soft tissues (Fig. 11.2). In the most severe cases, dense scar tissue obliterates the normal peripatellar recesses, suprapatellar pouch, intercondylar notch, and articular surfaces. The consequent pain and permanent loss of knee motion may lead to severe quadriceps atrophy, loss of patellar mobility, patellar tendon adaptive shortening, patella infera, and articular cartilage deterioration [49, 50]. The prevention of knee arthrofibrosis is paramount and preferred over using the currently available treatment options for this complication.

Performing ACL and other knee ligament reconstructions within a few weeks of the injury or before the resolution of swelling, pain, quadriceps muscle atrophy, abnormal gait mechanics, and motion limitations has been noted by many authors to correlate with postoperative knee motion problems [46, 184–190]. It appears that, in the majority of cases, delaying surgery until knee motion is regained, swelling is resolved, and a good quadriceps contraction is demonstrated is advantageous in decreasing the risk of postoperative arthrofibrosis. This is especially true in patients who demonstrate an exaggerated inflammatory response to the ACL injury that is characterized by pain, soft tissue edema, and redness and increased warmth to tissues surrounding the knee.

Modern rehabilitation programs incorporate immediate knee motion and muscle-strengthening exercises the day after surgery, both of which have been shown to be safe and not deleterious to healing grafts. Failure to obtain full knee motion will greatly hinder the patient's ability to reach other rehabilitation goals, and therefore, any problems achieving flexion and extension should be addressed during the early postoperative period. Our ROM program begins the first postoperative day and includes patellar mobilization (inferior, superior, medial, and lateral directions) to avoid an infrapatellar contracture (Fig. 11.3). Patients are expected to demonstrate 0–90° by the seventh day; those who fail to achieve this motion goal are placed into the treatment protocol shown in Table 11.8 [183]. The exercises and modalities described next to obtain gentle overpressure are usually successful in restoring full extension and flexion. For knee extension, a hanging weight regimen may be done in which the foot and ankle are propped on a towel or other devices to elevate the hamstrings and gastrocnemius (Fig. 11.4). This position is maintained for 10 min per session and repeated 4–8 times a day.

Fig. 11.3 Patellar mobilization (glides) are begun the first postoperative day in the (**a**) superior and inferior and (**b**) medial and lateral planes (Reprinted from Heckmann et al. [27])

Weight (up to 25 pounds, 11.3 kg) may be added to the distal thigh to provide further overpressure to stretch the posterior capsule. An extension board may also be effective if available. If problems persist, a drop-out cast is used for 24–36 h for continuous extension overpressure.

Flexion overpressure options include wall slides and commercially available modalities (Fig. 11.5). Patients who have difficulty achieving 90° by the fourth postoperative week require a gentle ranging of the knee under anesthesia as described elsewhere [183].

The senior author has reported on the complication of developmental patella infera that occurs after major knee injury or surgery, secondary to contracture of peripatellar and infrapatellar scar tissues and quadriceps weakness [49, 50, 183]. This condition may result in permanent shortening of the patellar tendon, patellofemoral arthritis, and severe functional limitations. To prevent this

Table 11.8 Protocols for limitation of knee motion [150]

Extension limitations
0° not achieved by seventh postoperative day
– Hanging weight exercise: prefer supine position; prop the foot and ankle on a towel or other devices to elevate the hamstrings and gastrocnemius to allow the knee to drop into full extension
Add 10 lb weight to the distal thigh to provide overpressure to stretch the posterior capsule
Maintain for 10–15 min and repeat 4–8×/day
Add more weight (up to 25 lb) if full extension is not achieved within a week
– Commercially available extension board
– Drop-out cast for 24–36 h, unless knee has >12° extension deficit with a hard block to terminal extension
>10° extension deficit third to fourth postoperative week
– Gentle manipulation under anesthesia
12° extension deficit and hard block to terminal extension sixth postoperative week
– Arthroscopic release of contracted scar tissues
Flexion limitations
90° not achieved by seventh postoperative day
– Rolling stool exercise: sit on a small stool close to the ground, flex the knee to its maximum position possible, and hold that position for 1–2 min. Then, gently roll the stool forward without moving the foot to achieve a few more degrees of flexion
– Wall slide exercise: lie on the back and place the foot of the reconstructed knee on a wall with the knee flexed. Use the foot of the opposite leg to gently slide the opposite foot and further flex the reconstructed knee in a gradual manner
– Commercially available knee flexion devices
90° not achieved by third to fourth postoperative week
– Gentle manipulation under anesthesia
< 90° flexion sixth postoperative week
– Arthroscopic release of contracted scar tissues

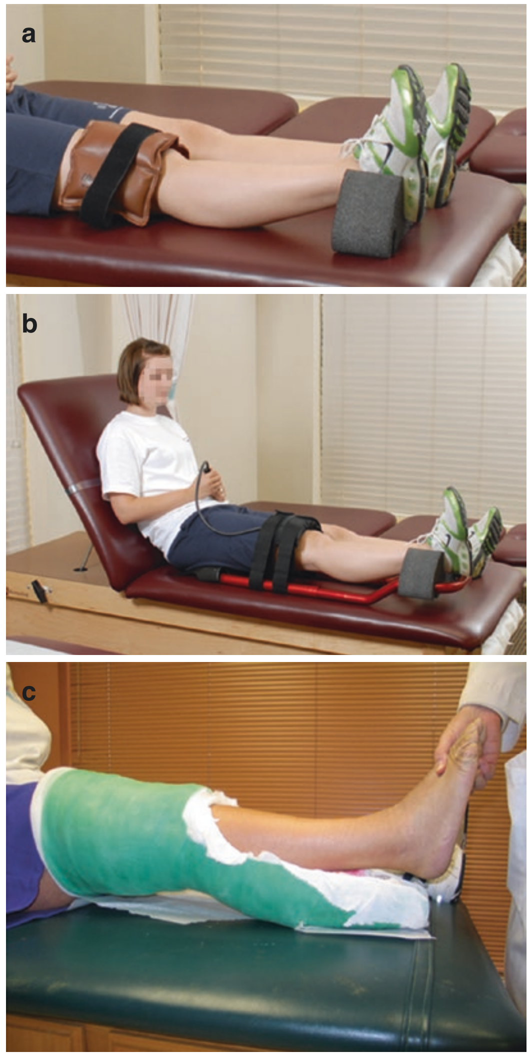


Fig. 11.4 Options to regain full knee extension include (**a**) hanging weights, (**b**) extension board, and for difficult cases, (**c**) a drop-out cast (Reprinted from Noyes and Barber-Westin [183])

problem, the steps previously described to prevent arthrofibrosis are taken before and after surgery. In addition, the patient is instructed preoperatively on the importance of achieving a voluntary quadriceps contraction as soon as possible after surgery, which is expected to occur by the second postoperative day. Patellar mobility is assessed weekly by the therapist to detect any early contracture. Serial lateral radiographs are taken to detect any decrease in patellar height for patients demonstrating limited patellar mobility or in whom an early arthrofibrotic response is detected (Fig. 11.6).

OKC extension exercises are begun after the first four postoperative weeks. Caution is warranted due to the potential problems these exercises may create for the healing graft and the patellofemoral joint. Resistance in the terminal phase of open kinetic chain extension (0–30°) is avoided as described previously. The patellofemoral joint must be monitored for changes in pain, swelling, and crepitus to avoid a patellar conversion in which painful patellofemoral crepitus develops with articular cartilage damage.

Fig. 11.5 Options to regain full knee flexion include (**a**) rolling stool exercise, (**b**) wall slides, (**c**) flexion seat, (**d**) knee flexion overpressure device, and (**e**) figure-four knee flexion overpressure exercise (Reprinted from Noyes and Barber-Westin [183])

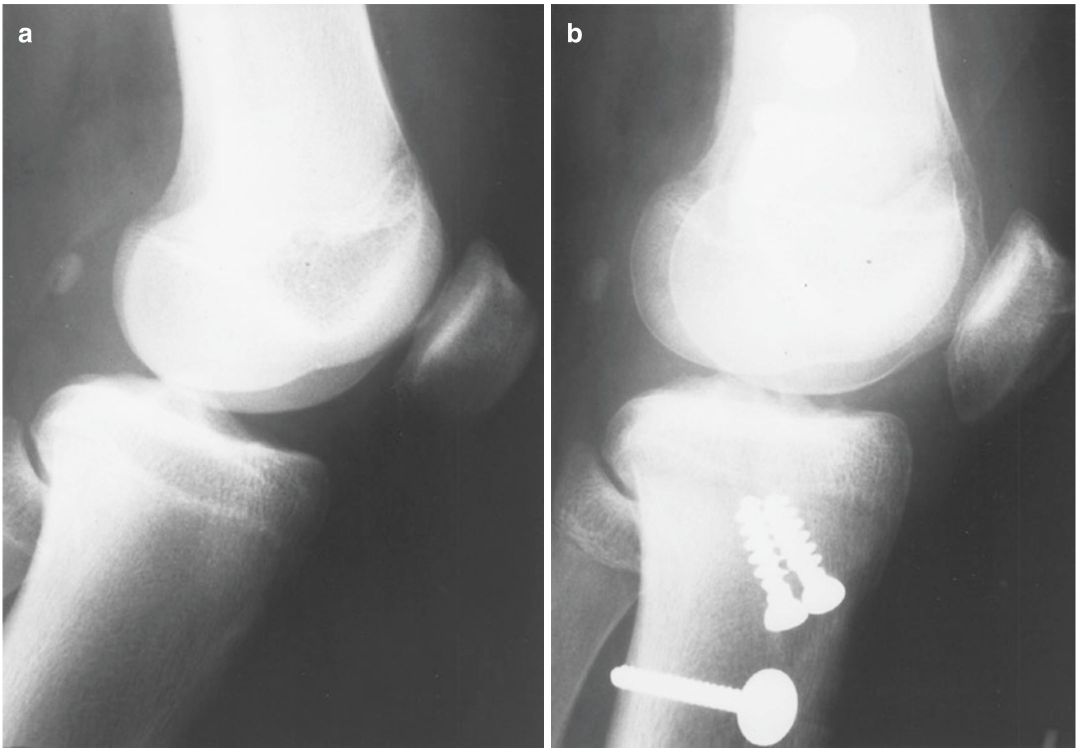


Fig. 11.6 Lateral radiographs document a 22% decrease in patellar vertical height ratio following a combined ACL reconstruction and medial meniscus repair in a 14-year-old female gymnast. (**a**) The injured knee before the reconstruction. (**b**) Four weeks postoperatively, the patient was referred to our center with significant quadriceps atrophy, difficulty performing knee motion exercises, and limited patellar mobility. The patient was treated with daily physical therapy and required an arthroscopic debridement, peripatellar release, lysis of adhesions, and removal of infrapatellar scar tissue. Nine months postoperatively, the patient had regained full knee motion, had no pain symptoms, and had returned to recreational activities. However, the patellar infera remained unchanged (Reprinted from Noyes et al. [50])

A rare but potentially severe problem is the onset postoperatively of complex regional pain syndrome (CRPS) [191]. Nomenclature relating to CRPS has varied over the years and has included Sudeck's atrophy, reflex sympathetic dystrophy (RSD), post-traumatic dystrophy, and causalgia. The disorder usually follows tissue injury or surgery to a limb (although it may have a spontaneous onset) that may be associated with sensory, vasomotor, sudomotor, motor, and dystrophic changes [192]. The pain is distinct in that it is out of proportion to the inciting event and may be accompanied by discoloration of skin, change in skin temperature, abnormal sweating, edema, and loss of the normal range of motion of the affected limb. The early diagnosis and treatment of this disorder is crucial because early management yields a more favorable outcome [193–196]. If not successfully managed, CRPS patients suffer a major loss of quality of life for several years [197] and will most likely experience psychological consequences of their chronic pain [198, 199]. The term *CRPS-I* indicates diagnostic criteria are present without major nerve damage, while the term *CRPS-II* indicates diagnostic criteria exist along with nerve injury, entrapment, or compression or the formation of a neuroma. The current diagnostic criteria for CRPS, known as the Budapest Criteria, are shown in Table 11.9 [201].

Several theories have been devised to explain the etiology and pathophysiology of CRPS [202–208], most of which discuss CRPS in

Table 11.9 Budapest clinical diagnostic criteria for complex regional pain syndrome (CRPS) [200]

General definition of the syndrome
CRPS describes an array of painful conditions that are characterized by a continuing (spontaneous and/or evoked) regional pain that is seemingly disproportionate in time or degree to the usual course of any known trauma or other lesions. The pain is regional (not in specific nerve territory or dermatome) and usually has a distal predominance of abnormal sensory, motor, sudomotor, vasomotor, and/or trophic findings. The syndrome shows variable progression over time
To make the clinical diagnosis of CRPS, the following criteria must be met
1. Continuing pain, which is disproportionate to any inciting event
2. Must report at least one symptom in *three of the four* following categories
Sensory: Reports of hyperesthesia and/or allodynia
Vasomotor: Reports of temperature asymmetry and/or skin color changes and/or skin color asymmetry
Sudomotor/edema: Reports of edema and/or sweating changes and/or sweating asymmetry
Motor/trophic: Reports of decreased range of motion and/or motor dysfunction (weakness, tremor, dystonia) and/or trophic changes (hair, nail, skin)
3. Must display at least one sign at time of evaluation in *two or more* of the following categories
Sensory: Evidence of hyperalgesia (to pinprick) and/or allodynia (to light touch and/or deep somatic pressure and/or joint movement)
Vasomotor: Evidence of temperature asymmetry (>1 °C) and/or skin color changes and/or asymmetry
Sudomotor/edema: Evidence of edema and/or sweating changes and/or sweating asymmetry
Motor/trophic: Evidence of decreased range of motion and/or motor dysfunction (weakness, tremor, dystonia) and/or trophic changes (hair, nail, skin)
4. There is no other diagnosis that better explains the signs and symptoms

general and not specifically as it relates to the knee joint [209]. Investigators typically agree that this disorder involves the central, autonomic, and somatic nervous systems, may be influenced by neurogenic inflammation and an immunologic response, creates central sensitization, and may induce cortical reorganization. In the chronic state, tissue ischemia/hypoxia may result from endothelial dysfunction and impaired circulation, and severe psychological distress and neuropsychological impairment may occur.

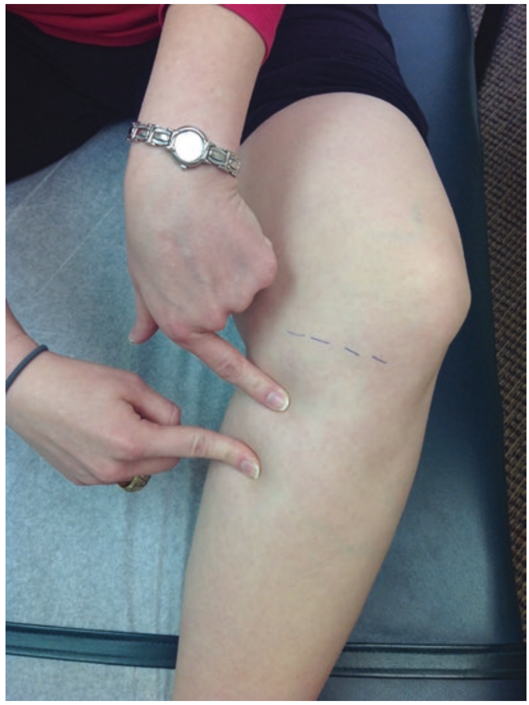


Fig. 11.7 Patient pointing to the painful areas along the regions of the infrapatellar nerve and the saphenous nerve. She was diagnosed with CRPS type II because her direct anterior below-knee trauma produced a nerve contusion and injury (Reprinted from Noyes and Barber-Westin [191])

Common self-reported symptoms include asymmetry in skin color, hyperesthesia (allodynia, hyperpathia), asymmetric edema, and motor changes. Frequent signs observed on physical examination are skin color asymmetry, hyperalgesia, decreased active range of motion, and motor changes. A classic finding is allodynia during the physical exam in which the patient describes the inability to tolerate pressure from bed sheets at night, clothing, and even air currents. The hallmark finding of CRPS is pain disproportionate to the inciting event, including pain more intense than expected, lasting longer than expected, and expanding beyond the dermatomal region of the extremity. The pain may be described as burning and shooting or as deep, constant, and aching (Figs. 11.7 and 11.8). Pain may worsen with aggressive physical therapy, weather changes (becoming colder), physical activity, and fear or agitation.

In patients with suspected nerve injuries or neuromas, a diagnostic nerve block is indicated

Fig. 11.8 Patient pointing to the site of skin hypersensitivity to touch and burning sensation on the anteromedial aspect of her knee. She was diagnosed with CRPS type I because no specific nerve damage was detected (Reprinted from Noyes and Barber-Westin [191])

[191]. In the knee, this usually involves the infrapatellar branch of the saphenous nerve and may also involve the medial retinacular nerve, the medial cutaneous nerve, and the lateral retinacular nerve. A lumbar sympathetic ganglion block is one tool used for both diagnosing and treating CRPS-I, although its use is controversial. MRI is done before a lumbar block to detect other possible triggers for pain such as a meniscus tear to avoid the necessity of this test. Treatment options vary and have been described in detail elsewhere [183].

Critical Points

- Recognize and treat complications early postoperatively.
- First postoperative week, watch for:
  - Infection
  - Deep venous thrombosis
  - Less than 0–90° knee motion
- Treat limitations of knee motion with overpressure program beginning seventh postoperative day.
- Gentle ranging of knee under anesthesia postoperative week 4 if 90° not obtained.
- Assess patellar mobility weekly; if there is any contracture, assess for patella infera.
- Continually watch for onset of patellofemoral pain or patellar tendinitis.
- Understand symptoms of complex regional pain syndrome.

11.4 Protocol for Primary ACL Bone-Patellar Tendon-Bone Autogenous Reconstruction: Early Return to Strenuous Activities

This rehabilitation protocol is used for patients who undergo primary ACL bone-patellar tendon-bone autogenous reconstruction and desire to return to strenuous sports or work activities as soon as possible after surgery. The overall goals for the early phases of rehabilitation are to control pain and swelling, regain ROM of at least

0–135°, resume full weight-bearing with a normal gait pattern, and recover adequate strength of the lower extremity and hip musculatures (Table 11.10).

The first postoperative week is a critical time period in regard to control of knee joint pain and swelling (Table 11.11). The patient must demonstrate an adequate quadriceps muscle contraction and begin immediate knee motion, patellar mobilization, and basic lower extremity muscle-strengthening exercises. Patients are encouraged to elevate the limb above their heart several times a day for the first 5–7 days. High-intensity electrical muscle stimulation, biofeedback, and cryotherapy are used as required to control pain and swelling, assist in achieving an adequate quadriceps contraction, and regain normal knee motion.

Patients begin passive knee motion exercises the first day postoperatively in a seated position for 10 min a session, 3–4 times a day (Fig. 11.9). The patella is mobilized in all four directions (medial, lateral, superior, inferior) initially by the therapist and then by the patient along with the knee motion exercises (Fig. 11.10).

A long-leg hinged brace may be used during the first few postoperative weeks to protect the patient in case of a fall, promote early comfortable weight-bearing, and encourage normal knee flexion during ambulation. Derotation or functional knee braces are not routinely prescribed upon return to full activities.

Balance and proprioceptive training are begun the first postoperative week with weight shifting. Double- and single-leg balance exercises in the stance position are beneficial early postoperatively. Walking over cups or cones is done forward, backward, and sideways (Fig. 11.11a). Half foam rolls are also used as part of the gait

Table 11.10 Goals of each phase of rehabilitation [150]

Phase	Goals
I Weeks 1–2	Control pain, inflammation, effusion ROM minimum: 0–110° Achieve adequate quadriceps contraction, patellar mobility 50% weight-bearing
II Weeks 3–4	Control pain, inflammation, effusion ROM minimum: 0–120° Muscle control: 3/5 Full weight-bearing Lachman, KT-2000 arthrometer test ≤3 mm increase over opposite side
III Weeks 5–6	No or minimal pain, effusion ROM: 0–135° Full weight-bearing, normal gait, no pain, good patellar mobility Muscle control: 4/5 Recognition of complications (motion loss, pain syndrome, increased anteroposterior tibial displacement), patellofemoral changes
IV Weeks 7–8	Manual muscle test hamstrings, quadriceps, hip: 4/5 No pain, swelling, patellofemoral crepitus Normal patellar mobility, knee motion Lachman, KT-2000 arthrometer test ≤3 mm increase over opposite side
V Weeks 9–12	Isokinetic test (isometric, 12 weeks): ≤30% deficit quadriceps and hamstrings No pain, swelling, patellofemoral crepitus Lachman, KT-2000 arthrometer test ≤3 mm increase over opposite side
VI Weeks 13–26	Isokinetic test (isometric and 180°/s and 300°/s): <20% deficit quadriceps and hamstrings, test monthly No pain, swelling, patellofemoral crepitus Lachman, KT-2000 arthrometer test ≤3 mm increase over opposite side Single-leg hop tests (any 2 tests): ≤15% deficit compared to uninvolved limb
VII Week 27–beyond	Isokinetic test (180°/s and 300°/s): <10% deficit quadriceps and hamstrings, test monthly No pain, swelling, patellofemoral crepitus Lachman, KT-2000 arthrometer test ≤3 mm increase over opposite side Single-leg hop tests (any 2 tests): ≤15% deficit compared to uninvolved limb

ROM range of motion, *KT* knee arthrometer

Table 11.11 Cincinnati SportsMedicine and Orthopaedic Center rehabilitation protocol for primary ACL reconstruction: early return to strenuous activities

	P.O. weeks					P.O. month			
	1–2	3–4	5–6	7–8	9–12	4	5	6	7–12
Brace: long-leg hinged	X	(X)							
Range of motion minimum goals									
0–110°	X								
0–120°		X							
0–135°			X						
Weight-bearing									
½ body weight	X								
Full		X							
Patella mobilization	X	X	X						
Modalities									
Electrical muscle stimulation	X	X	X						
Biofeedback	X	X	X						
Pain/edema management (cryotherapy)	X	X	X	X	X	X	X	X	X
Stretching									
Hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X	X	X	X	X
Strengthening									
Quadriceps isometrics, straight leg raises, active knee extension	X	X	X	X	X				
Closed chain: gait retraining, toe raises, heel raises, wall sits, mini-squats	X	X	X	X	X				
Knee flexion hamstring curls (0–90°)	X	X	X	X	X	X	X	X	X
Knee extension quadriceps (90–30°)	X	X	X	X	X	X	X	X	X
Hip abduction-adduction, multi-hip	X	X	X	X	X	X	X	X	X
Leg press (80–10°)	X	X	X	X	X	X	X	X	X
Upper body weight training			X	X	X	X	X	X	X
Dynamic hip and core training			X	X	X	X	X	X	X
Balance/proprioceptive training									
Weight shifting, cup walking, BBS	X	X							
BBS, BAPS, single-leg stance		X	X	X	X	X	X	X	
Step-ups			X	X	X				
Resistance band walking, perturbation training, ball toss mini-trampoline				X	X				
Conditioning									
Upper body cycle	X	X	X						
Bike (stationary)		X	X	X	X	X	X	X	X
Aquatic program		X	X	X	X	X	X	X	X
Stair climbing machine (low resistance, low stroke)			X	X	X	X	X	X	X
Ski machine (short stride, level, low resistance)			X	X	X	X	X	X	X
Swimming (kicking)				X	X	X	X	X	X
Walking				X	X	X	X	X	X
Elliptical machine					X	X	X	X	X
Running and agility program					(X)	X	X	X	X
Functional (plyometric) training, sports-specific drills						(X)	X	X	X
Full sports								X	X

BAPS Biomechanical Ankle Platform System, *BBS* Biodex Balance System. Brace: (X) if needed
Running, functional training: (X) based on symptoms and isokinetic testing goals [27]

retraining and balance program (Fig. 11.11b). This exercise helps the patient develop balance and dynamic muscular control required to maintain an upright position and be able to walk from one end of the roll to the other. Developing a center of balance, limb symmetry, quadriceps control in midstance, and postural positioning are benefits obtained from this type of training.

Fig. 11.9 Passive range of knee motion exercises done by (**a**–**c**) the patient or (**d**) the therapist (Reprinted from Heckmann et al. [150])

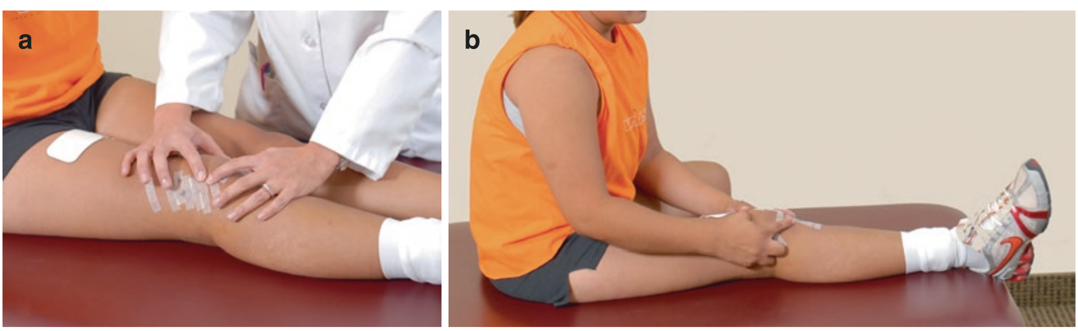


Fig. 11.10 Patella mobilization performed by (**a**) the therapist or (**b**) the patient (Reprinted from Heckmann et al. [150])

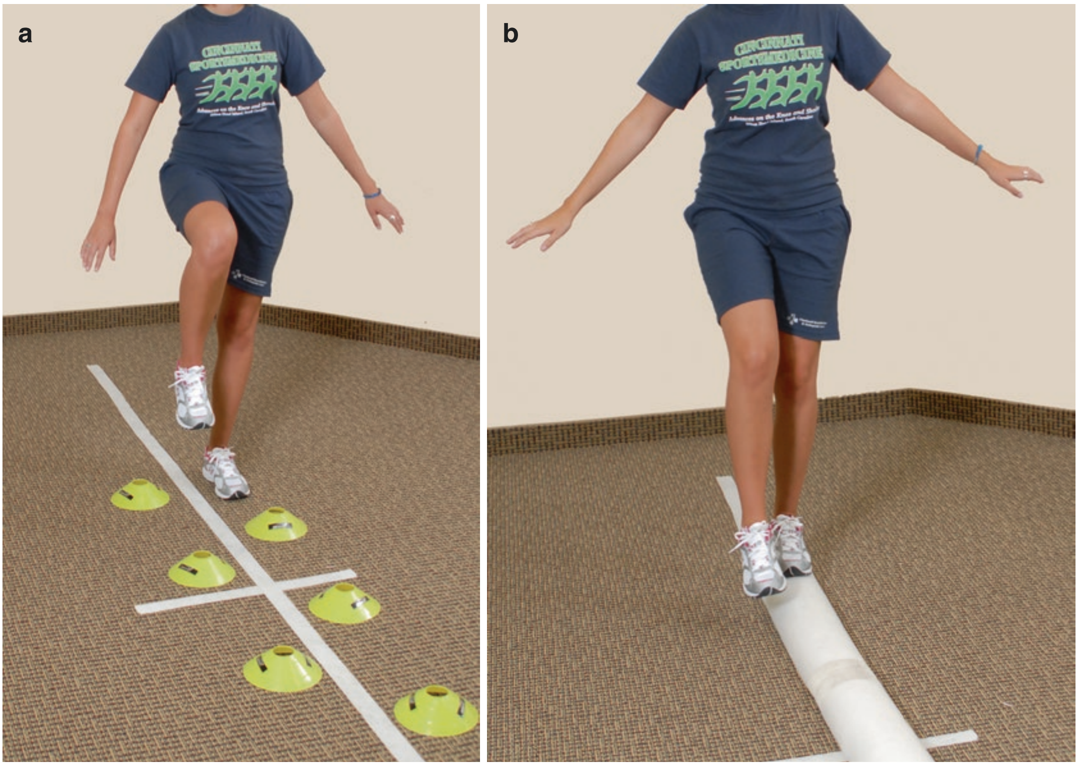


Fig. 11.11 The early gait retraining and balance program includes walking (**a**) over cups or cones and (**b**) on half foam rolls (Reprinted from Heckmann et al. [150])

During weeks 5–6, lateral step-ups are done on a step or surface that is 2–4 inches (5.08–10.16 cm) high. Perturbation training techniques are begun at approximately weeks 7–8 to further promote balance and neuromuscular control. The therapist stands behind the patient and disrupts his/her body posture and position and the platform periodically to enhance dynamic knee stability (Fig. 11.12).

Lower extremity-strengthening exercises begun the first day after surgery include isometrics, straight leg raises in the four planes of hip movement, and active-assisted knee extension. CKC exercises are initiated the first postoperative week, including mini-squats and the leg press machine (Fig. 11.13). Hamstring curls are begun with Velcro ankle weights within the first few weeks and eventually advanced to weight machines. Hamstring strength is critical to the overall success of the rehabilitation program due to the role that this musculature plays in the dynamic stabilization of the knee joint. OKC extension exercises are also begun after the first four postoperative weeks to further develop quadriceps muscle strength.

A full lower extremity-strengthening program is critical for early and long-term success of the rehabilitation program. Other muscle groups included in this routine are the hip abductors, adductors, flexors, and extensors. These muscle groups are exercised by using a multi-hip or cable system or a hip abductor/adductor machine (Fig. 11.14), performing a side-lying “clam” exercise with (or without) a resistance band (Fig. 11.15), walking with exaggerated hip flexion with (or without) a resistance band

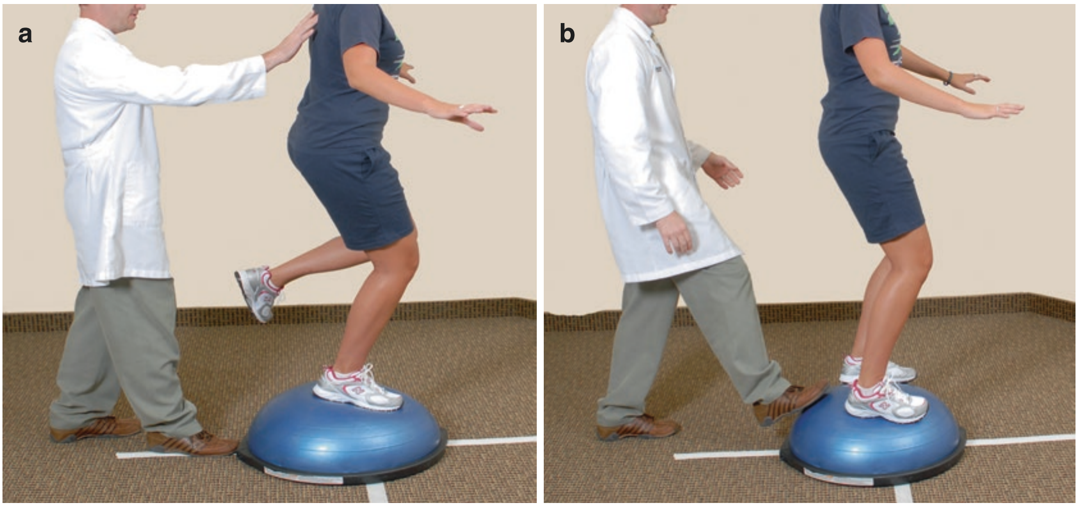


Fig. 11.12 Perturbation training performed by using direct contact with either the (**a**) patient or (**b**) platform (Reprinted from Heckmann et al. [150])

(Fig. 11.16), and ambulating with side-stepping with (or without) a resistance band, making sure the patient lands on a flexed knee. Strength of the gastrocnemius and soleus muscles is a key component for both early ambulation and progression to the running program and is recovered using toe raises and heel raises, beginning with both feet together (Fig. 11.17) and processing to single-leg raises. Importantly, upper body weight training and dynamic hip and core training are initiated 5–6 weeks postoperatively.

Muscle-strengthening exercises are progressed as shown in Table 11.5. The amount of weight should be gradually increased according to patient tolerance. Patients should also perform upper extremity and core strengthening depending on their overall activity goals. Single-leg balance exercises may incorporate a mini-trampoline or unstable platform, as these devices promote greater dynamic limb control than that required to stand on a stable surface (Fig. 11.18a, b). To provide a greater challenge, patients may assume the single-leg stance position and throw and catch a weighted ball against an inverted mini-trampoline until fatigue occurs (Fig. 11.18c). They may also perform controlled single-leg hops in specific directions by balancing first on the normal contralateral limb (Fig. 11.19a), hopping and landing on the reconstructed limb in a controlled manner (Fig. 11.19b), and then returning to the starting position, balanced on the normal limb (Fig. 11.19c).

Aerobic conditioning may begin the first week with an upper body cycle machine (Biodex Medical Systems, Shirley, NY) if available. Stationary bicycling is begun during the third week. Water walking may be initiated when the surgical wound has healed. Cross-country ski and stair climbing machines are permitted during the fifth to sixth postoperative week. Protection against high stresses to the patellofemoral joint is strongly advocated. During bicycling, the seat height is adjusted to its highest level based on patient body size and a low resistance level is used initially. Stair climbing machines are adjusted to produce a short step with low resistance. Early goals of these programs include facilitation of full range of motion, gait retraining, and cardiovascular reconditioning. At postoperative week 9, patients are

Fig. 11.13 Closed kinetic chain exercises begun the first postoperative week include (**a**) mini-squats, (**b**) wall sits, and (**c**) the leg press machine (Reprinted from Heckmann et al. [150])

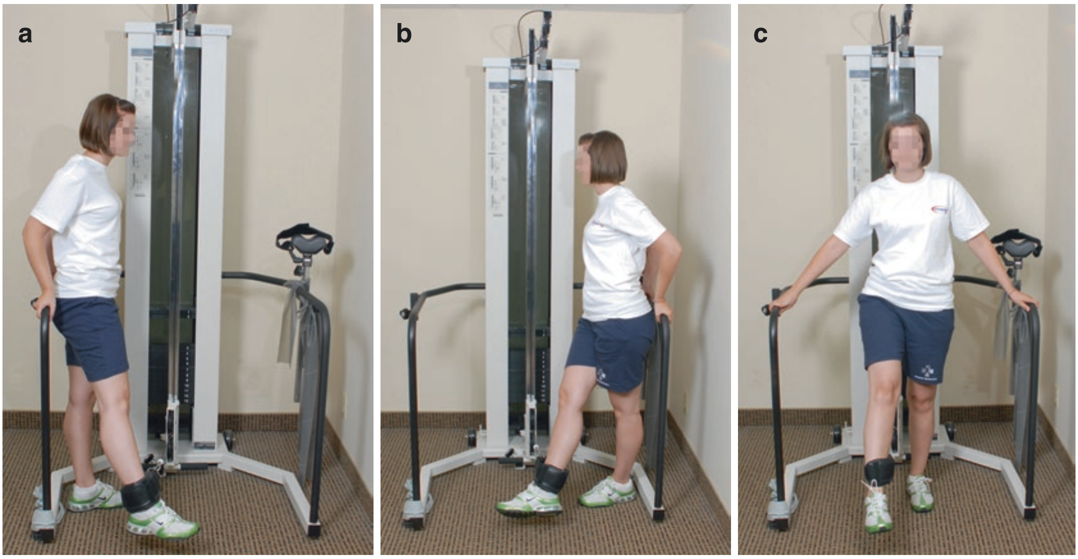


Fig. 11.14 The hip (**a**) abductors, (**b**) adductors, and (**c**) flexor muscle groups exercised on a cable system machine (Reprinted from Heckmann et al. [150])

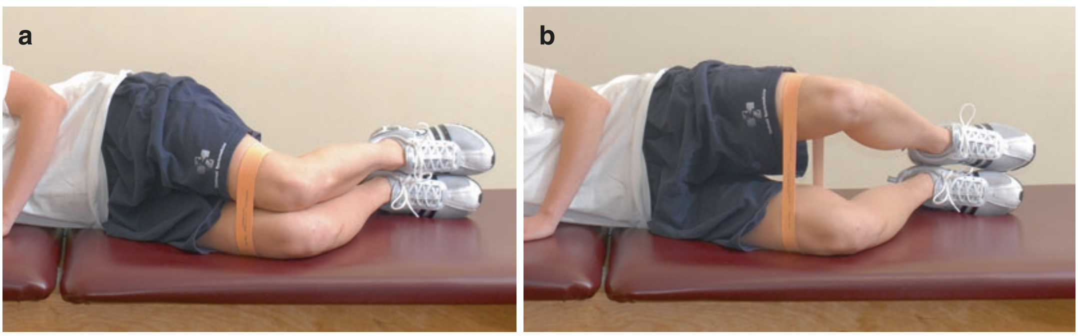


Fig. 11.15 The hip abductors exercised using a side-lying "clam" exercise which may be performed with (**a**, **b**) or without a resistance band (Reprinted from Heckmann et al. [150])

encouraged to spend at least 3 days a week in 20–30-min sessions using available equipment and facilities.

The remainder of the rehabilitation program, including programs for running, agility training, plyometric training, sports-specific drills, and criteria to return to full unrestricted sports, has been described elsewhere [27]. Chapter 14 details basic and advanced neuromuscular training techniques, including the use of Sportsmetrics as end-stage rehabilitation. This program is mandatory in our practice for all athletes regardless of gender to prepare them to return to high-risk sports involving cutting, pivoting, and repeated jumping.

11.5 Protocol with Delayed Parameters for Revision ACL Reconstruction, Multi-ligament Reconstruction, Allografts, and Complex Knees

We developed a postoperative rehabilitation protocol (Table 11.12) for patients who undergo ACL revision, ACL allograft (primary or revision) reconstruction, and major concomitant operative procedures (complex meniscus repairs or transplants, other ligament reconstructions, articular cartilage restorative procedures, patellofemoral realignment procedures, or osteotomies) or who have noteworthy articular cartilage

Fig. 11.16 Walking with exaggerated hip flexion may be done with or without a resistance band (Reprinted from Heckmann et al. [150])

damage. Allografts are only used in our practice in patients requiring multi-ligament reconstruction due to the increase in failure rate compared with autografts reported in multiple studies [10, 12, 15].

This protocol incorporates delays in return of full weight-bearing and knee flexion; initiation of certain strengthening, conditioning, running, and agility drills; and return to unrestricted activities. The amount of weight patients are allowed to bear depends on the concomitant operative procedures performed as well as evaluation of postoperative pain and swelling, quadriceps muscle control, and ROM. The majority of patients are weaned from crutch support between postoperative weeks 6–8.

Allowance of knee flexion of at least 135° is delayed according to the concomitant procedure performed. A long-leg hinged knee brace is used for approximately the first 8 weeks in all patients except those who undergo a posterolateral procedure. The brace provides protection and support to the healing tissues and assists with patient comfort during this time period.

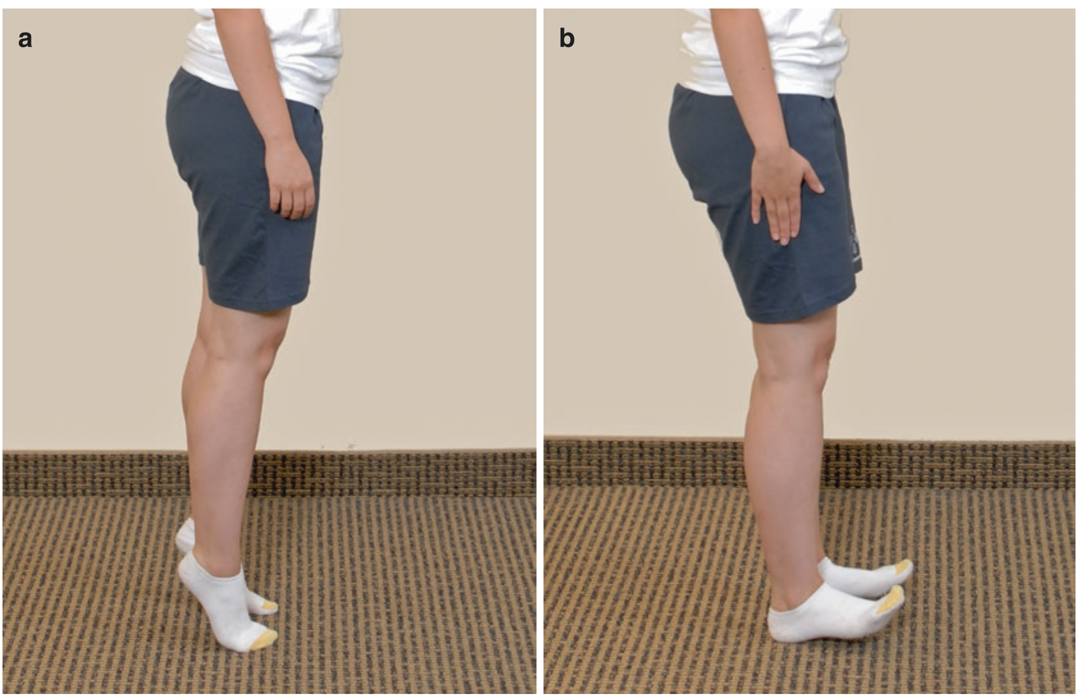


Fig. 11.17 Strength of the gastrocnemius and soleus muscles initially recovered using (**a**) toe raises and (**b**) heel raises (Reprinted from Heckmann et al. [150])

Fig. 11.18 Single-leg balance exercises done on (**a**, **b**) unstable platforms and (**c**) including the patient throwing and catching a weighted ball against an inverted mini-trampoline (Reprinted from Heckmann et al. [150])

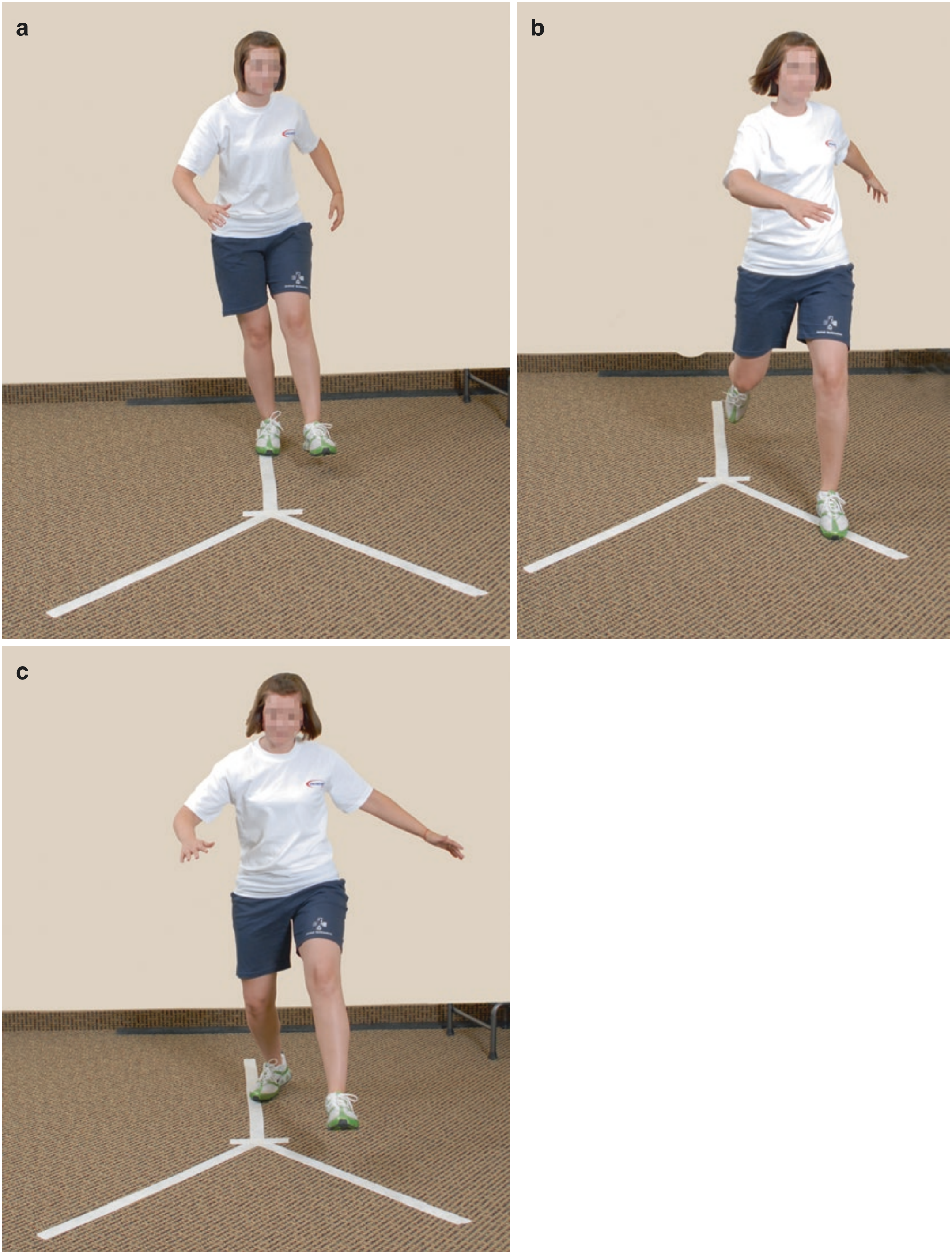


Fig. 11.19 Controlled single-leg directional hopping and balancing (**a**–**c**) (Reprinted from Heckmann et al. [150])

Table 11.12 Cincinnati SportsMedicine and Orthopaedic Center rehabilitation protocol for ACL reconstruction: revision knees, allografts, and complex knees

	P.O. week					P.O. month			
	1–2	3–4	5–6	7–8	9–12	4	5	6	7–12
Brace: long-leg hinged and functional	X	X	X	X	(X)			X	X
Range of motion minimum goals									
0–90°	X	X							
0–120°			X						
0–135°				X					
Weight-bearing									
Toe touch	X								
¼ to ½ body weight		X							
¾ to full body weight			X						
Patella mobilization	X	X	X	X					
Modalities									
Electrical muscle stimulation	X	X	X	X					
Biofeedback	X	X	X						
Pain/edema management (cryotherapy)	X	X	X	X	X	X	X	X	X
Stretching									
Hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X	X	X	X	X
Strengthening									
Quadriceps-hamstrings isometrics, co-contraction, straight leg raises, active knee extension	X	X	X	X	X				
Closed-chain: gait retraining, toe-raises, wall-sits, mini-squats	X	X	X	X	X	X			
Knee flexion hamstring curls (0–90°)			X	X	X	X	X	X	X
Knee extension quadriceps (90–30°)			X	X	X	X	X	X	X
Hip abduction-adduction, multi-hip			X	X	X	X	X	X	X
Leg press (70–10°)			X	X	X	X	X	X	X
Balance/proprioceptive training									
Weight-shifting, cup-walking	X	X	X	X	X				
BBS, BAPS, perturbation training, balance board, mini-trampoline					X	X	X	X	X
Conditioning									
Upper body cycle		X	X	X					
Bike (stationary)			X	X	X	X	X	X	X
Aquatic program			X	X	X	X	X	X	X
Swimming (kicking)					X	X	X	X	X
Walking					X	X	X	X	X
Stair climbing machine				X	X	X	X	X	X
Ski machine				X	X	X	X	X	X
Elliptical machine				X	X	X	X	X	X
Running: straight								(X)	(X)
Agility program, plyometric training, sports-specific drills									(X)
Full sports									(X)

BAPS Biomechanical Ankle Platform System, *BBS* Biodex Balance System. Brace: (X) if needed
Running, agility training, plyometric training, full sports: (X) based on symptoms, condition of the articular cartilage, and isokinetic testing goals [27]

Knees that undergo a posterolateral reconstructive procedure are placed into a bivalved long-leg cast for the first 4 weeks [210]. The patient removes the cast to perform ROM exercises several times a day and is instructed to reach 0° of extension, but to avoid hyperextension. Patients who undergo a concomitant proximal patellar realignment are allowed 0–75° for the first 2 postoperative weeks. Flexion is slowly advanced to 135° by the eighth week. Knee flexion is also initially limited in knees that undergo a concomitant posterior cruciate ligament reconstruction [211] or complex meniscus repair [212].

Knee extension is limited in individuals who have abnormal hyperextension (≥10°) with physiologic laxity to 0–5° for approximately 3 weeks to allow for sufficient healing before stress is applied to push for 0°.

Modifications in strengthening, conditioning, and strenuous training are based on the concomitant procedures performed. Return to running is delayed until at least the sixth postoperative month to allow for healing of all repaired and reconstructed tissues and return of joint and muscle function. It is our opinion that allografts have a delay in maturation compared to autografts and that the resultant time constraints postoperatively in terms of release to full activity are empiric at present. Evaluation is a key component to allow initiation of the functional program, which includes the assessment of symptoms and examination of knee motion, muscle strength, and ligament stability. In patients following this protocol, return to full activity is not usually expected to occur until postoperative months 9–12. Consideration of use of a derotation or functional brace is given in patients who undergo ACL revision or multi-ligament reconstruction or who demonstrate an increase in anteroposterior displacement postoperatively of >3 mm compared with the contralateral limb. In addition, patients who are apprehensive in returning to strenuous activities or who experience a subjective sensation of instability are candidates for functional bracing.

References

1. Shaarani SR, O'Hare C, Quinn A, Moyna N, Moran R, O'Byrne JM. Effect of prehabilitation on the outcome of anterior cruciate ligament reconstruction. Am J Sports Med. 2013;41(9):2117–27. https://doi.org/10.1177/0363546513493594.
2. Eitzen I, Moksnes H, Snyder-Mackler L, Risberg MA. A progressive 5-week exercise therapy program leads to significant improvement in knee function early after anterior cruciate ligament injury. J Orthop Sports Phys Ther. 2010;40(11):705–21. https://doi.org/10.2519/jospt.2010.3345.
3. de Valk EJ, Moen MH, Winters M, Bakker EW, Tamminga R, van der Hoeven H. Preoperative patient and injury factors of successful rehabilitation after anterior cruciate ligament reconstruction with single-bundle techniques. Arthroscopy. 2013;29(11):1879–95. https://doi.org/10.1016/j.arthro.2013.07.273.
4. Silkman C, McKeon J. The effect of preoperative quadriceps strength on strength and function after anterior cruciate ligament reconstruction. J Sport Rehabil. 2012;21(1):89–93.
5. van Grinsven S, van Cingel RE, Holla CJ, van Loon CJ. Evidence-based rehabilitation following anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2010;18(8):1128–44. https://doi.org/10.1007/s00167-009-1027-2.
6. Quelard B, Sonnery-Cottet B, Zayni R, Ogassawara R, Prost T, Chambat P. Preoperative factors correlating with prolonged range of motion deficit after anterior cruciate ligament reconstruction. Am J Sports Med. 2010;38(10):2034–9. https://doi.org/10.1177/0363546510370198.
7. Logerstedt D, Lynch A, Axe MJ, Snyder-Mackler L. Symmetry restoration and functional recovery before and after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2013;21(4):859–68. https://doi.org/10.1007/s00167-012-1929-2.
8. Logerstedt D, Lynch A, Axe MJ, Snyder-Mackler L. Pre-operative quadriceps strength predicts IKDC 2000 scores 6 months after anterior cruciate ligament reconstruction. Knee. 2013;20(3):208–12. https://doi.org/10.1016/j.knee.2012.07.011.
9. Faltstrom A, Hagglund M, Magnusson H, Forssblad M, Kvist J. Predictors for additional anterior cruciate ligament reconstruction: data from the Swedish national ACL register. Knee Surg Sports Traumatol Arthrosc. 2016;24(3):885–94. https://doi.org/10.1007/s00167-014-3406-6.
10. Hettrich CM, Dunn WR, Reinke EK, Group M, Spindler KP. The rate of subsequent surgery and predictors after anterior cruciate ligament reconstruction: two- and 6-year follow-up results from a multicenter cohort. Am J Sports Med. 2013;41(7):1534–40. https://doi.org/10.1177/0363546513490277.
11. Hui C, Salmon LJ, Kok A, Maeno S, Linklater J, Pinczewski LA. Fifteen-year outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft for "isolated" anterior cruciate ligament tear. Am J Sports Med. 2011;39(1):89–98. https://doi.org/10.1177/0363546510379975.
12. Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, Consortium M, Spindler KP. Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: prospective analysis of 2488 primary ACL reconstructions from the MOON Cohort. Am J Sports Med. 2015;43(7):1583–90. https://doi.org/10.1177/0363546515578836.
13. Kamien PM, Hydrick JM, Replogle WH, Go LT, Barrett GR. Age, graft size, and Tegner activity level as predictors of failure in anterior cruciate ligament reconstruction with hamstring autograft.

Am J Sports Med. 2013;41(8):1808–12. https://doi.org/10.1177/0363546513493896.

14. Magnussen RA, Lawrence JT, West RL, Toth AP, Taylor DC, Garrett WE. Graft size and patient age are predictors of early revision after anterior cruciate ligament reconstruction with hamstring autograft. Arthroscopy. 2012;28(4):526–31. https://doi.org/10.1016/j.arthro.2011.11.024.
15. Maletis GB, Inacio MC, Funahashi TT. Risk factors associated with revision and contralateral anterior cruciate ligament reconstructions in the Kaiser Permanente ACLR registry. Am J Sports Med. 2015;43(3):641–7. https://doi.org/10.1177/0363546514561745.
16. Morgan MD, Salmon LJ, Waller A, Roe JP, Pinczewski LA. Fifteen-year survival of endoscopic anterior cruciate ligament reconstruction in patients aged 18 years and younger. Am J Sports Med. 2016;44(2):384–92. https://doi.org/10.1177/0363546515623032.
17. Park SY, Oh H, Park S, Lee JH, Lee SH, Yoon KH. Factors predicting hamstring tendon autograft diameters and resulting failure rates after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2013;21(5):1111–8. https://doi.org/10.1007/s00167-012-2085-4.
18. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. Am J Sports Med. 2014;42(7):1567–73. https://doi.org/10.1177/0363546514530088.
19. Persson A, Fjeldsgaard K, Gjertsen JE, Kjellsen AB, Engebretsen L, Hole RM, Fevang JM. Increased risk of revision with hamstring tendon grafts compared with patellar tendon grafts after anterior cruciate ligament reconstruction: a study of 12,643 patients from the Norwegian Cruciate Ligament Registry, 2004-2012. Am J Sports Med. 2014;42(2):285–91. https://doi.org/10.1177/0363546513511419.
20. Ponce BA, Cain EL Jr, Pflugner R, Fleisig GS, Young BL, Boohaker HA, Swain TA, Andrews JR, Dugas JR. Risk factors for revision anterior cruciate ligament reconstruction. J Knee Surg. 2016;29(4):329–36. https://doi.org/10.1055/s-0035-1554925.
21. Schlumberger M, Schuster P, Schulz M, Immendorfer M, Mayer P, Bartholoma J, Richter J. Traumatic graft rupture after primary and revision anterior cruciate ligament reconstruction: retrospective analysis of incidence and risk factors in 2915 cases. Knee Surg Sports Traumatol Arthrosc. 2015;25(5):1535–41. https://doi.org/10.1007/s00167-015-3699-0.
22. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med. 2009;37(2):246–51.
23. Thompson S, Salmon L, Waller A, Linklater J, Roe J, Pinczewski L. Twenty-year outcomes of a longitudinal prospective evaluation of isolated endoscopic anterior cruciate ligament reconstruction with patellar tendon autografts. Am J Sports Med. 2015;43(9):2164–74. https://doi.org/10.1177/0363546515591263.
24. Webster KE, Feller JA. Exploring the high reinjury rate in younger patients undergoing anterior cruciate ligament reconstruction. Am J Sports Med. 2016;44(11):2827–32. https://doi.org/10.1177/0363546516651845.
25. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Am J Sports Med. 2016;44(7):1861–76. https://doi.org/10.1177/0363546515621554.
26. Barber-Westin SD, Noyes FR. Scientific basis of rehabilitation after anterior cruciate ligament autogenous reconstruction. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 268–92. https://doi.org/10.1016/b978-0-323-32903-3.00010-x.
27. Heckmann TP, Noyes FR, Barber-Westin SD. Rehabilitation of primary and revision anterior cruciate ligament reconstruction. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 293–329. https://doi.org/10.1016/b978-0-323-32903-3.00011-1.
28. Barber-Westin SD, Noyes FR, Heckmann TP, Shaffer BL. The effect of exercise and rehabilitation on anterior-posterior knee displacements after anterior cruciate ligament autograft reconstruction. Am J Sports Med. 1999;27(1):84–93.
29. Barber-Westin SD, Noyes FR. The effect of rehabilitation and return to activity on anterior-posterior knee displacements after anterior cruciate ligament reconstruction. Am J Sports Med. 1993;21(2):264–70.
30. Noyes FR, Barber-Westin SD. Anterior cruciate ligament primary reconstruction: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 137–220. https://doi.org/10.1016/b978-0-323-32903-3.00007-x.
31. Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: graft options and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 221–57. https://doi.org/10.1016/b978-0-323-32903-3.00008-1.
32. Noyes FR, Mangine RE, Barber S. Early knee motion after open and arthroscopic anterior cruciate ligament reconstruction. Am J Sports Med. 1987;15(2):149–60.
33. Noyes FR, Berrios-Torres S, Barber-Westin SD, Heckmann TP. Prevention of permanent arthrofibrosis after anterior cruciate ligament reconstruction alone or combined with associated procedures: a prospective study in 443 knees. Knee Surg Sports Traumatol Arthrosc. 2000;8(4):196–206.

34. Palmieri-Smith RM, Kreinbrink J, Ashton-Miller JA, Wojtys EM. Quadriceps inhibition induced by an experimental knee joint effusion affects knee joint mechanics during a single-legged drop landing. Am J Sports Med. 2007;35(8):1269–75.
35. Torry MR, Decker MJ, Viola RW, O'Connor DD, Steadman JR. Intra-articular knee joint effusion induces quadriceps avoidance gait patterns. Clin Biomech. 2000;15(3):147–59.
36. Torry MR, Decker MJ, Millett PJ, Steadman JR, Sterett WI. The effects of knee joint effusion on quadriceps electromyography during jogging. J Sports Sci Med. 2005;4:1–8.
37. Jensen K, Graf BK. The effects of knee effusion on quadriceps strength and knee intraarticular pressure. Arthroscopy. 1993;9(1):52–6.
38. Palmieri-Smith RM, Thomas AC, Wojtys EM. Maximizing quadriceps strength after ACL reconstruction. Clin Sports Med. 2008;27(3):405–24. https://doi.org/10.1016/j.csm.2008.02.001.
39. Kuenze C, Hart JM. Cryotherapy to treat persistent muscle weakness after joint injury. Phys Sportsmed. 2010;38(3):38–44. https://doi.org/10.3810/psm.2010.10.1806.
40. Ito Y, Deie M, Adachi N, Kobayashi K, Kanaya A, Miyamoto A, Nakasa T, Ochi M. A prospective study of 3-day versus 2-week immobilization period after anterior cruciate ligament reconstruction. Knee. 2007;14(1):34–8. https://doi.org/10.1016/j.knee.2006.10.004.
41. Henriksson M, Rockborn P, Good L. Range of motion training in brace vs. plaster immobilization after anterior cruciate ligament reconstruction: a prospective randomized comparison with a 2-year follow-up. Scand J Med Sci Sports. 2002;12(2):73–80.
42. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, part 2. Am J Sports Med. 2005;33(11):1751–67.
43. Isberg J, Faxen E, Brandsson S, Eriksson BI, Karrholm J, Karlsson J. Early active extension after anterior cruciate ligament reconstruction does not result in increased laxity of the knee. Knee Surg Sports Traumatol Arthrosc. 2006;14(11):1108–15. https://doi.org/10.1007/s00167-006-0138-2.
44. Kruse LM, Gray B, Wright RW. Rehabilitation after anterior cruciate ligament reconstruction: a systematic review. J Bone Joint Surg. 2012;94(19):1737–48. https://doi.org/10.2106/JBJS.K.01246.
45. Noyes FR, Butler DL, Paulos LE, Grood ES. Intra-articular cruciate reconstruction. I: perspectives on graft strength, vascularization, and immediate motion after replacement. Clin Orthop Relat Res. 1983;172:71–7.
46. Cosgarea AJ, Sebastianelli WJ, DeHaven KE. Prevention of arthrofibrosis after anterior cruciate ligament reconstruction using the central third patellar tendon autograft. Am J Sports Med. 1995;23(1):87–92.
47. Skyhar MJ, Danzig LA, Hargens AR, Akeson WH. Nutrition of the anterior cruciate ligament. Effects of continuous passive motion. Am J Sports Med. 1985;13(6):415–8.
48. Paulos LE, Wnorowski DC, Greenwald AE. Infrapatellar contracture syndrome. Diagnosis, treatment, and long-term followup. Am J Sports Med. 1994;22(4):440–9.
49. Noyes FR, Wojtys EM. The early recognition, diagnosis and treatment of the patella infera syndrome. In: Tullos HS, editor. Instructional course lectures, vol. XL. Rosemont: AAOS; 1991. p. 233–47.
50. Noyes FR, Wojtys EM, Marshall MT. The early diagnosis and treatment of developmental patella infera syndrome. Clin Orthop Relat Res. 1991;265:241–52.
51. Noyes FR, Torvik PJ, Hyde WB, DeLucas JL. Biomechanics of ligament failure. II. An analysis of immobilization, exercise, and reconditioning effects in primates. J Bone Joint Surg. 1974;56(7):1406–18.
52. Wilk KE, Macrina LC, Cain EL, Dugas JR, Andrews JR. Recent advances in the rehabilitation of anterior cruciate ligament injuries. J Orthop Sports Phys Ther. 2012;42(3):153–71. https://doi.org/10.2519/jospt.2012.3741.
53. Culvenor AG, Lai CC, Gabbe BJ, Makdissi M, Collins NJ, Vicenzino B, Morris HG, Crossley KM. Patellofemoral osteoarthritis is prevalent and associated with worse symptoms and function after hamstring tendon autograft ACL reconstruction. Br J Sports Med. 2014;48(6):435–9. https://doi.org/10.1136/bjsports-2013-092975.
54. Neuman P, Kostogiannis I, Friden T, Roos H, Dahlberg LE, Englund M. Patellofemoral osteoarthritis 15 years after anterior cruciate ligament injury--a prospective cohort study. Osteoarthr Cartil. 2009;17(3):284–90. https://doi.org/10.1016/j.joca.2008.07.005.
55. Shelbourne KD, Urch SE, Gray T, Freeman H. Loss of normal knee motion after anterior cruciate ligament reconstruction is associated with radiographic arthritic changes after surgery. Am J Sports Med. 2012;40(1):108–13. https://doi.org/10.1177/0363546511423639.
56. Shelbourne KD, Benner RW, Gray T. Results of anterior cruciate ligament reconstruction with patellar tendon autografts: objective factors associated with the development of osteoarthritis at 20 to 33 years after surgery. Am J Sports Med. 2017;45(12):2730–8. https://doi.org/10.1177/0363546517718827.
57. Tyler TF, McHugh MP, Gleim GW, Nicholas SJ. The effect of immediate weightbearing after anterior cruciate ligament reconstruction. Clin Orthop Relat Res. 1998;357:141–8.
58. Wright RW, Preston E, Fleming BC, Amendola A, Andrish JT, Bergfeld JA, Dunn WR, Kaeding C, Kuhn JE, Marx RG, McCarty EC, Parker RC, Spindler KP, Wolcott M, Wolf BR, Williams GN. A systematic review of anterior cruciate ligament reconstruction rehabilitation: part I: continuous passive motion, early weight bearing, postopera-

tive bracing, and home-based rehabilitation. J Knee Surg. 2008;21(3):217–24.
59. Fukuda TY, Fingerhut D, Moreira VC, Camarini PM, Scodeller NF, Duarte A Jr, Martinelli M, Bryk FF. Open kinetic chain exercises in a restricted range of motion after anterior cruciate ligament reconstruction: a randomized controlled clinical trial. Am J Sports Med. 2013;41(4):788–94. https://doi.org/10.1177/0363546513476482.
60. Beynnon BD, Johnson RJ, Naud S, Fleming BC, Abate JA, Brattbakk B, Nichols CE. Accelerated versus nonaccelerated rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind investigation evaluating knee joint laxity using roentgen stereophotogrammetric analysis. Am J Sports Med. 2011;39(12):2536–48. https://doi.org/10.1177/0363546511422349.
61. Sekir U, Gur H, Akova B. Early versus late start of isokinetic hamstring-strengthening exercise after anterior cruciate ligament reconstruction with patellar tendon graft. Am J Sports Med. 2010;38(3):492–500. https://doi.org/10.1177/0363546509349490.
62. Harilainen A, Sandelin J. Post-operative use of knee brace in bone-tendon-bone patellar tendon anterior cruciate ligament reconstruction: 5-year follow-up results of a randomized prospective study. Scand J Med Sci Sports. 2006;16(1):14–8. https://doi.org/10.1111/j.1600-0838.2004.00435.x.
63. Hasegawa S, Kobayashi M, Arai R, Tamaki A, Nakamura T, Moritani T. Effect of early implementation of electrical muscle stimulation to prevent muscle atrophy and weakness in patients after anterior cruciate ligament reconstruction. J Electromyogr Kinesiol. 2011;21(4):622–30. https://doi.org/10.1016/j.jelekin.2011.01.005.
64. Feil S, Newell J, Minogue C, Paessler HH. The effectiveness of supplementing a standard rehabilitation program with superimposed neuromuscular electrical stimulation after anterior cruciate ligament reconstruction: a prospective, randomized, single-blind study. Am J Sports Med. 2011;39(6):1238–47. https://doi.org/10.1177/0363546510396180.
65. Wilk KE, Chmielewski TL. Neuromuscular retraining after anterior cruciate ligament reconstruction. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Philadelphia: Saunders; 2010. p. 337–56.
66. Snyder-Mackler L, Ladin Z, Schepsis AA, Young JC. Electrical stimulation of the thigh muscles after reconstruction of the anterior cruciate ligament. Effects of electrically elicited contraction of the quadriceps femoris and hamstring muscles on gait and on strength of the thigh muscles. J Bone Joint Surg. 1991;73(7):1025–36.
67. Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. A prospective, randomized clinical trial of electrical stimulation. J Bone Joint Surg. 1995;77(8):1166–73.
68. Delitto A, Rose SJ, McKowen JM, Lehman RC, Thomas JA, Shively RA. Electrical stimulation versus voluntary exercise in strengthening thigh musculature after anterior cruciate ligament surgery. Phys Ther. 1988;68(5):660–3.
69. Wright RW, Preston E, Fleming BC, Amendola A, Andrish JT, Bergfeld JA, Dunn WR, Kaeding C, Kuhn JE, Marx RG, McCarty EC, Parker RC, Spindler KP, Wolcott M, Wolf BR, Williams GN. A systematic review of anterior cruciate ligament reconstruction rehabilitation: part II: open versus closed kinetic chain exercises, neuromuscular electrical stimulation, accelerated rehabilitation, and miscellaneous topics. J Knee Surg. 2008;21(3):225–34.
70. Imoto AM, Peccin S, Almeida GJ, Saconato H, Atallah AN. Effectiveness of electrical stimulation on rehabilitation after ligament and meniscal injuries: a systematic review. Sao Paulo Med J. 2011;129(6):414–23.
71. Draper V. Electromyographic biofeedback and recovery of quadriceps femoris muscle function following anterior cruciate ligament reconstruction. Phys Ther. 1990;70(1):11–7.
72. Draper V, Ballard L. Electrical stimulation versus electromyographic biofeedback in the recovery of quadriceps femoris muscle function following anterior cruciate ligament surgery. Phys Ther. 1991;71(6):455–61.
73. Christanell F, Hoser C, Huber R, Fink C, Luomajoki H. The influence of electromyographic biofeedback therapy on knee extension following anterior cruciate ligament reconstruction: a randomized controlled trial. Sports Med Arthrosc Rehabil Ther Technol. 2012;4(1):41. https://doi.org/10.1186/1758-2555-4-41.
74. Perraton L, Clark R, Crossley K, Pua YH, Whitehead T, Morris H, Telianidis S, Bryant A. Impaired voluntary quadriceps force control following anterior cruciate ligament reconstruction: relationship with knee function. Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1424–31. https://doi.org/10.1007/s00167-015-3937-5.
75. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2012;42(9):750–9. https://doi.org/10.2519/jospt.2012.4194.
76. Hsiao SF, Chou PH, Hsu HC, Lue YJ. Changes of muscle mechanics associated with anterior cruciate ligament deficiency and reconstruction. J Strength Cond Res. 2014;28(2):390–400. https://doi.org/10.1519/JSC.0b013e3182986cc1.
77. Hart JM, Pietrosimone B, Hertel J, Ingersoll CD. Quadriceps activation following knee injuries: a systematic review. J Athl Train. 2010;45(1):87–97. https://doi.org/10.4085/1062-6050-45.1.87.
78. Thomas AC, Villwock M, Wojtys EM, Palmieri-Smith RM. Lower extremity muscle strength after anterior cruciate ligament injury and reconstruc-

tion. J Athl Train. 2013;48(5):610–20. https://doi.org/10.4085/1062-6050-48.3.23.
79. de Jong SN, van Caspel DR, van Haeff MJ, Saris DB. Functional assessment and muscle strength before and after reconstruction of chronic anterior cruciate ligament lesions. Arthroscopy. 2007;23(1):21–8.
80. Hiemstra LA, Webber S, MacDonald PB, Kriellaars DJ. Contralateral limb strength deficits after anterior cruciate ligament reconstruction using a hamstring tendon graft. Clin Biomech. 2007;22(5):543–50. https://doi.org/10.1016/j.clinbiomech.2007.01.009.
81. Karanikas K, Arampatzis A, Bruggemann GP. Motor task and muscle strength followed different adaptation patterns after anterior cruciate ligament reconstruction. Eur J Phys Rehabil Med. 2009;45(1):37–45.
82. Konishi Y, Ikeda K, Nishino A, Sunaga M, Aihara Y, Fukubayashi T. Relationship between quadriceps femoris muscle volume and muscle torque after anterior cruciate ligament repair. Scand J Med Sci Sports. 2007;17(6):656–61. https://doi.org/10.1111/j.1600-0838.2006.00619.x.
83. Konishi Y, Oda T, Tsukazaki S, Kinugasa R, Hirose N, Fukubayashi T. Relationship between quadriceps femoris muscle volume and muscle torque after anterior cruciate ligament rupture. Knee Surg Sports Traumatol Arthrosc. 2011;19(4):641–5. https://doi.org/10.1007/s00167-010-1324-9.
84. Konishi Y, Fukubayashi T. Relationship between muscle volume and muscle torque of the hamstrings after anterior cruciate ligament reconstruction. J Sci Med Sport. 2010;13(1):101–5. https://doi.org/10.1016/j.jsams.2008.08.001.
85. Moisala AS, Jarvela T, Kannus P, Jarvinen M. Muscle strength evaluations after ACL reconstruction. Int J Sports Med. 2007;28(10):868–72. https://doi.org/10.1055/s-2007-964912.
86. Palmieri-Smith RM, Thomas AC. A neuromuscular mechanism of posttraumatic osteoarthritis associated with ACL injury. Exerc Sport Sci Rev. 2009;37(3):147–53. https://doi.org/10.1097/JES.0b013e3181aa6669.
87. Cuomo P, Rama KR, Bull AM, Amis AA. The effects of different tensioning strategies on knee laxity and graft tension after double-bundle anterior cruciate ligament reconstruction. Am J Sports Med. 2007;35(12):2083–90.
88. Oiestad BE, Holm I, Gunderson R, Myklebust G, Risberg MA. Quadriceps muscle weakness after anterior cruciate ligament reconstruction: a risk factor for knee osteoarthritis? Arthritis Care Res. 2010;62(12):1706–14. https://doi.org/10.1002/acr.20299.
89. Keays SL, Newcombe PA, Bullock-Saxton JE, Bullock MI, Keays AC. Factors involved in the development of osteoarthritis after anterior cruciate ligament surgery. Am J Sports Med. 2010;38(3):455–63. https://doi.org/10.1177/0363546509350914.
90. Tourville TW, Jarrell KM, Naud S, Slauterbeck JR, Johnson RJ, Beynnon BD. Relationship between isokinetic strength and tibiofemoral joint space width changes after anterior cruciate ligament reconstruction. Am J Sports Med. 2014;42(2):302–11. https://doi.org/10.1177/0363546513510672.
91. Haggmark T, Jansson E, Eriksson E. Fiber type area and metabolic potential of the thigh muscle in man after knee surgery and immobilization. Int J Sports Med. 1981;2(1):12–7.
92. Young A, Hughes I, Round JM, Edwards RH. The effect of knee injury on the number of muscle fibres in the human quadriceps femoris. Clin Sci. 1982;62(2):227–34.
93. Baugher WH, Warren RF, Marshall JL, Joseph A. Quadriceps atrophy in the anterior cruciate insufficient knee. Am J Sports Med. 1984;12(3):192–5.
94. Elmqvist LG, Lorentzon R, Johansson C, Fugl-Meyer AR. Does a torn anterior cruciate ligament lead to change in the central nervous drive of the knee extensors? Eur J Appl Physiol Occup Physiol. 1988;58(1-2):203–7.
95. Lorentzon R, Elmqvist LG, Sjostrom M, Fagerlund M, Fuglmeyer AR. Thigh musculature in relation to chronic anterior cruciate ligament tear: muscle size, morphology, and mechanical output before reconstruction. Am J Sports Med. 1989;17(3):423–9.
96. Solomonow M, Baratta R, Zhou BH, Shoji H, Bose W, Beck C, D'Ambrosia R. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. Am J Sports Med. 1987;15(3):207–13.
97. Johansson H, Sjolander P, Sojka P. Activity in receptor afferents from the anterior cruciate ligament evokes reflex effects on fusimotor neurones. Neurosci Res. 1990;8(1):54–9.
98. Johansson H, Sjolander P, Sojka P. A sensory role for the cruciate ligaments. Clin Orthop Relat Res. 1991;268:161–78.
99. Johansson H, Sjolander P, Sojka P. Receptors in the knee joint ligaments and their role in the biomechanics of the joint. Crit Rev Biomed Eng. 1991;18(5):341–68.
100. Sojka P, Sjolander P, Johansson H, Djupsjoback M. Influence from stretch-sensitive receptors in the collateral ligaments of the knee joint on the gamma-muscle-spindle systems of flexor and extensor muscles. Neurosci Res. 1991;11(1):55–62.
101. Snyder-Mackler L, Binder-Macleod SA, Williams PR. Fatigability of human quadriceps femoris muscle following anterior cruciate ligament reconstruction. Med Sci Sports Exerc. 1994;25(7):783–9.
102. Konishi Y, Fukubayashi T, Takeshita D. Mechanism of quadriceps femoris muscle weakness in patients with anterior cruciate ligament reconstruction. Scand J Med Sci Sports. 2002;12(6):371–5.
103. Konishi Y, Konishi H, Fukubayashi T. Gamma loop dysfunction in quadriceps on the contralateral side in patients with ruptured ACL. Med Sci Sports Exerc. 2003;35(6):897–900. https://doi.org/10.1249/01.MSS.0000069754.07541.D2.
104. Snyder-Mackler L, De Luca PF, Williams PR, Eastlack ME, Bartolozzi AR. Reflex inhibition of

the quadriceps femoris muscle after injury or reconstruction of the anterior cruciate ligament. J Bone Joint Surg. 1994;76(4):555–60.
105. Hopkins JT, Ingersoll CD. Arthrogenic muscle inhibition: a limiting factor in joint rehabilitation. J Sport Rehabil. 2000;9:135–59.
106. Krishnan C, Williams GN. Factors explaining chronic knee extensor strength deficits after ACL reconstruction. J Orthop Res. 2011;29(5):633–40. https://doi.org/10.1002/jor.21316.
107. Mendias CL, Lynch EB, Davis ME, Sibilsky Enselman ER, Harning JA, Dewolf PD, Makki TA, Bedi A. Changes in circulating biomarkers of muscle atrophy, inflammation, and cartilage turnover in patients undergoing anterior cruciate ligament reconstruction and rehabilitation. Am J Sports Med. 2013;41(8):1819–26. https://doi.org/10.1177/0363546513490651.
108. Lepley AS, Ericksen HM, Sohn DH, Pietrosimone BG. Contributions of neural excitability and voluntary activation to quadriceps muscle strength following anterior cruciate ligament reconstruction. Knee. 2014;21(3):736–42. https://doi.org/10.1016/j.knee.2014.02.008.
109. Reilly DT, Martens M. Experimental analysis of the quadriceps muscle force and patello-femoral joint reaction force for various activities. Acta Orthop Scand. 1972;43(2):126–37.
110. Smith AJ. Estimates of muscle and joint force at the knee and ankle during jumping activities. J Hum Mov Stud. 1975;1:78–86.
111. Escamilla RF, Zheng N, Macleod TD, Brent Edwards W, Imamura R, Hreljac A, Fleisig GS, Wilk KE, Moorman CT, Andrews JR. Patellofemoral joint force and stress during the wall squat and one-leg squat. Med Sci Sports Exerc. 2009;41(4):879–88. https://doi.org/10.1249/MSS.0b013e31818e7ead.
112. Steinkamp LA, Dillingham MF, Markel MD, Hill JA, Kaufman KR. Biomechanical considerations in patellofemoral joint rehabilitation. Am J Sports Med. 1993;21(3):438–44.
113. Karasel S, Akpinar B, Gulbahar S, Baydar M, El O, Pinar H, Tatari H, Karaoglan O, Akalin E. Clinical and functional outcomes and proprioception after a modified accelerated rehabilitation program following anterior cruciate ligament reconstruction with patellar tendon autograft. Acta Orthop Traumatol Turc. 2010;44(3):220–8. https://doi.org/10.3944/AOTT.2010.2293.
114. Gadea F, Monnot D, Quelard B, Mortati R, Thaunat M, Fayard JM, Sonnery-Cottet B. Knee pain after anterior cruciate ligament reconstruction: evaluation of a rehabilitation protocol. Eur J Orthop Surg Traumatol. 2014;24(5):789–95. https://doi.org/10.1007/s00590-013-1248-4.
115. Doucette SA, Child DD. The effect of open and closed chain exercise and knee joint position on patellar tracking in lateral patellar compression syndrome. J Orthop Sports Phys Ther. 1996;23(2):104–10. https://doi.org/10.2519/jospt.1996.23.2.104.
116. Escamilla RF, Fleisig GS, Zheng N, Lander JE, Barrentine SW, Andrews JR, Bergemann BW, Moorman CT. Effects of technique variations on knee biomechanics during the squat and leg press. Med Sci Sports Exerc. 2001;33(9):1552–66.
117. Escamilla RF, Fleisig GS, Zheng N, Barrentine SW, Wilk KE, Andrews JR. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. Med Sci Sports Exerc. 1998;30(4):556–69.
118. Harvie D, O'Leary T, Kumar S. A systematic review of randomized controlled trials on exercise parameters in the treatment of patellofemoral pain: what works? J Multidiscip Healthc. 2011;4:383–92. https://doi.org/10.2147/JMDH.S24595.
119. Chinkulprasert C, Vachalathiti R, Powers CM. Patellofemoral joint forces and stress during forward step-up, lateral step-up, and forward step-down exercises. J Orthop Sports Phys Ther. 2011;41(4):241–8. https://doi.org/10.2519/jospt.2011.3408.
120. Beynnon BD, Johnson RJ, Fleming BC. The science of anterior cruciate ligament rehabilitation. Clin Orthop Relat Res. 2002;402:9–20.
121. Beynnon B, Howe JG, Pope MH, Johnson RJ, Fleming BC. The measurement of anterior cruciate ligament strain in vivo. Int Orthop. 1992;16(1):1–12.
122. Beynnon BD, Fleming BC, Johnson RJ, Nichols CE, Renstrom PA, Pope MH. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. Am J Sports Med. 1995;23(1):24–34.
123. Beynnon BD, Johnson RJ, Fleming BC, Stankewich CJ, Renstrom PA, Nichols CE. The strain behavior of the anterior cruciate ligament during squatting and active flexion-extension. A comparison of an open and a closed kinetic chain exercise. Am J Sports Med. 1997;25(6):823–9.
124. Beynnon BD, Fleming BC. Anterior cruciate ligament strain in-vivo: a review of previous work. J Biomech. 1998;31(6):519–25.
125. Heijne A, Fleming BC, Renstrom PA, Peura GD, Beynnon BD, Werner S. Strain on the anterior cruciate ligament during closed kinetic chain exercises. Med Sci Sports Exerc. 2004;36(6):935–41.
126. Fleming BC, Beynnon BD, Renstrom PA, Peura GD, Nichols CE, Johnson RJ. The strain behavior of the anterior cruciate ligament during bicycling. An in vivo study. Am J Sports Med. 1998;26(1):109–18.
127. Fleming BC, Beynnon BD, Renstrom PA, Johnson RJ, Nichols CE, Peura GD, Uh BS. The strain behavior of the anterior cruciate ligament during stair climbing: an in vivo study. Arthroscopy. 1999;15(2):185–91.
128. Fleming BC, Oksendahl H, Beynnon BD. Open- or closed-kinetic chain exercises after anterior cruciate ligament reconstruction? Exerc Sport Sci Rev. 2005;33(3):134–40.
129. Fleming BC, Ohlen G, Renstrom PA, Peura GD, Beynnon BD, Badger GJ. The effects of compressive load and knee joint torque on peak anterior cruciate ligament strains. Am J Sports Med. 2003;31(5):701–7.

130. Escamilla RF, Macleod TD, Wilk KE, Paulos L, Andrews JR. Anterior cruciate ligament strain and tensile forces for weight-bearing and non-weight-bearing exercises: a guide to exercise selection. J Orthop Sports Phys Ther. 2012;42(3):208–20. https://doi.org/10.2519/jospt.2012.3768.
131. Tagesson S, Oberg B, Kvist J. Tibial translation and muscle activation during rehabilitation exercises 5 weeks after anterior cruciate ligament reconstruction. Scand J Med Sci Sports. 2010;20(1):154–64. https://doi.org/10.1111/j.1600-0838.2009.00903.x.
132. Toutoungi DE, Lu TW, Leardini A, Catani F, O'Connor JJ. Cruciate ligament forces in the human knee during rehabilitation exercises. Clin Biomech. 2000;15(3):176–87.
133. Ohkoshi Y, Yasuda K, Kaneda K, Wada T, Yamanaka M. Biomechanical analysis of rehabilitation in the standing position. Am J Sports Med. 1991;19(6):605–11.
134. Kulas AS, Hortobagyi T, DeVita P. Trunk position modulates anterior cruciate ligament forces and strains during a single-leg squat. Clin Biomech. 2012;27(1):16–21. https://doi.org/10.1016/j.clinbiomech.2011.07.009.
135. Perry MC, Morrissey MC, King JB, Morrissey D, Earnshaw P. Effects of closed versus open kinetic chain knee extensor resistance training on knee laxity and leg function in patients during the 8- to 14-week post-operative period after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2005;13(5):357–69.
136. Beynnon BD, Uh BS, Johnson RJ, Abate JA, Nichols CE, Fleming BC, Poole AR, Roos H. Rehabilitation after anterior cruciate ligament reconstruction. A prospective, randomized, double-blind comparison of programs administered over 2 different time periods. Am J Sports Med. 2005;33(3):347–59.
137. Mikkelsen C, Werner S, Eriksson E. Closed kinetic chain alone compared to combined open and closed kinetic chain exercises for quadriceps strengthening after anterior cruciate ligament reconstruction with respect to return to sports: a prospective matched follow-up study. Knee Surg Sports Traumatol Arthrosc. 2000;8(6):337–42.
138. Heijne A, Werner S. Early versus late start of open kinetic chain quadriceps exercises after ACL reconstruction with patellar tendon or hamstring grafts: a prospective randomized outcome study. Knee Surg Sports Traumatol Arthrosc. 2007;15(4):402–14. https://doi.org/10.1007/s00167-006-0246-z.
139. Shaw T, Williams MT, Chipchase LS. Do early quadriceps exercises affect the outcome of ACL reconstruction? A randomised controlled trial. Aust J Physiother. 2005;51(1):9–17.
140. Begalle RL, Distefano LJ, Blackburn T, Padua DA. Quadriceps and hamstrings coactivation during common therapeutic exercises. J Athl Train. 2012;47(4):396–405. https://doi.org/10.4085/1062-6050-47.4.01.
141. Farrokhi S, Pollard CD, Souza RB, Chen YJ, Reischl S, Powers CM. Trunk position influences the kinematics, kinetics, and muscle activity of the lead lower extremity during the forward lunge exercise. J Orthop Sports Phys Ther. 2008;38(7):403–9. https://doi.org/10.2519/jospt.2008.2634.
142. Ayotte NW, Stetts DM, Keenan G, Greenway EH. Electromyographical analysis of selected lower extremity muscles during 5 unilateral weight-bearing exercises. J Orthop Sports Phys Ther. 2007;37(2):48–55.
143. Ekstrom RA, Donatelli RA, Carp KC. Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. J Orthop Sports Phys Ther. 2007;37(12):754–62. https://doi.org/10.2519/jospt.2007.2471.
144. Matheson JW, Kernozek TW, Fater DC, Davies GJ. Electromyographic activity and applied load during seated quadriceps exercises. Med Sci Sports Exerc. 2001;33(10):1713–25.
145. Stensdotter AK, Hodges PW, Mellor R, Sundelin G, Hager-Ross C. Quadriceps activation in closed and in open kinetic chain exercise. Med Sci Sports Exerc. 2003;35(12):2043–7.
146. Beutler AI, Cooper LW, Kirkendall DT, Garrett WE Jr. Electromyographic analysis of single-leg, closed chain exercises: implications for rehabilitation after anterior cruciate ligament reconstruction. J Athl Train. 2002;37(1):13–8.
147. Kvist J, Gillquist J. Sagittal plane knee translation and electromyographic activity during closed and open kinetic chain exercises in anterior cruciate ligament-deficient patients and control subjects. Am J Sports Med. 2001;29(1):72–82.
148. Kvist J, Karlberg C, Gerdle B, Gillquist J. Anterior tibial translation during different isokinetic quadriceps torque in anterior cruciate ligament deficient and nonimpaired individuals. J Orthop Sports Phys Ther. 2001;31(1):4–15.
149. Wilk KE, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR, Boyd ML. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. Am J Sports Med. 1996;24(4):518–27.
150. Heckmann TP, Noyes FR, Barber-Westin S. Rehabilitation after ACL reconstruction. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete. 2nd ed. New York: Springer; 2018. p. 505–35. https://doi.org/10.1007/978-3-662-56558-2_22.
151. Gerber JP, Marcus RL, Dibble LE, Greis PE, LaStayo PC. Early application of negative work via eccentric ergometry following anterior cruciate ligament reconstruction: a case report. J Orthop Sports Phys Ther. 2006;36(5):298–307.
152. Gerber JP, Marcus RL, Dibble LE, Greis PE, Burks RT, Lastayo PC. Safety, feasibility, and efficacy of negative work exercise via eccentric muscle activity following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2007;37(1):10–8.
153. LaStayo PC, Woolf JM, Lewek MD, Snyder-Mackler L, Reich T, Lindstedt SL. Eccentric muscle

contractions: their contribution to injury, prevention, rehabilitation, and sport. J Orthop Sports Phys Ther. 2003;33(10):557–71.

154. Gerber JP, Marcus RL, Dibble LE, Greis PE, Burks RT, LaStayo PC. Effects of early progressive eccentric exercise on muscle structure after anterior cruciate ligament reconstruction. J Bone Joint Surg. 2007;89(3):559–70.
155. Gerber JP, Marcus RL, Dibble LE, Greis PE, Burks RT, LaStayo PC. Effects of early progressive eccentric exercise on muscle size and function after anterior cruciate ligament reconstruction: a 1-year follow-up study of a randomized clinical trial. Phys Ther. 2009;89(1):51–9. https://doi.org/10.2522/ptj.20070189.
156. Brasileiro JS, Pinto OM, Avila MA, Salvini TF. Functional and morphological changes in the quadriceps muscle induced by eccentric training after ACL reconstruction. Rev Bras Fisioter. 2011;15(4):284–90.
157. Papandreou M, Billis E, Papathanasiou G, Spyropoulos P, Papaioannou N. Cross-exercise on quadriceps deficit after ACL reconstruction. J Knee Surg. 2013;26(1):51–8. https://doi.org/10.1055/s-0032-1313744.
158. Barber-Westin S, Noyes FR. Blood flow-restricted training for lower extremity muscle weakness due to knee pathology: a systematic review. Sports Health. 2018;11(1):69–83. https://doi.org/10.1177/1941738118811337.
159. Ohta H, Kurosawa H, Ikeda H, Iwase Y, Satou N, Nakamura S. Low-load resistance muscular training with moderate restriction of blood flow after anterior cruciate ligament reconstruction. Acta Orthop Scand. 2003;74(1):62–8. https://doi.org/10.1080/00016470310013680.
160. Takarada Y, Takazawa H, Ishii N. Applications of vascular occlusion diminish disuse atrophy of knee extensor muscles. Med Sci Sports Exerc. 2000;32(12):2035–9.
161. Iversen E, Rostad V, Larmo A. Intermittent blood flow restriction does not reduce atrophy following anterior cruciate ligament reconstruction. J Sport Health Sci. 2016;5:115–8.
162. Wilk KE. Restoration of proprioception and neuromuscular control following ACL injury and surgery. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete: causes, impacts, and conditioning programs. 2nd ed. New York: Springer; 2018.
163. Muaidi QI, Nicholson LL, Refshauge KM, Adams RD, Roe JP. Effect of anterior cruciate ligament injury and reconstruction on proprioceptive acuity of knee rotation in the transverse plane. Am J Sports Med. 2009;37(8):1618–26. https://doi.org/10.1177/0363546509332429.
164. Magyar MO, Knoll Z, Kiss RM. Effect of medial meniscus tear and partial meniscectomy on balancing capacity in response to sudden unidirectional perturbation. J Electromyogr Kinesiol. 2012;22(3):440–5. https://doi.org/10.1016/j.jelekin.2012.01.010.
165. Malliou P, Gioftsidou A, Pafis G, Rokka S, Kofotolis N, Mavromoustakos S, Godolias G. Proprioception and functional deficits of partial meniscectomized knees. Eur J Phys Rehabil Med. 2012;48(2):231–6.
166. Goetschius J, Kuenze CM, Saliba S, Hart JM. Reposition acuity and postural control after exercise in anterior cruciate ligament reconstructed knees. Med Sci Sports Exerc. 2013;45(12):2314–21. https://doi.org/10.1249/MSS.0b013e31829bc6ae.
167. Alonso AC, Greve JM, Camanho GL. Evaluating the center of gravity of dislocations in soccer players with and without reconstruction of the anterior cruciate ligament using a balance platform. Clinics. 2009;64(3):163–70.
168. Howells BE, Ardern CL, Webster KE. Is postural control restored following anterior cruciate ligament reconstruction? A systematic review. Knee Surg Sports Traumatol Arthrosc. 2011;19(7):1168–77. https://doi.org/10.1007/s00167-011-1444-x.
169. Webster KA, Gribble PA. Time to stabilization of anterior cruciate ligament-reconstructed versus healthy knees in National Collegiate Athletic Association Division I female athletes. J Athl Train. 2010;45(6):580–5. https://doi.org/10.4085/1062-6050-45.6.580.
170. Delahunt E, Sweeney L, Chawke M, Kelleher J, Murphy K, Patterson M, Prendiville A. Lower limb kinematic alterations during drop vertical jumps in female athletes who have undergone anterior cruciate ligament reconstruction. J Orthop Res. 2012;30(1):72–8. https://doi.org/10.1002/jor.21504.
171. Mohammadi F, Salavati M, Akhbari B, Mazaheri M, Khorrami M, Negahban H. Static and dynamic postural control in competitive athletes after anterior cruciate ligament reconstruction and controls. Knee Surg Sports Traumatol Arthrosc. 2012;20(8):1603–10. https://doi.org/10.1007/s00167-011-1806-4.
172. Negahban H, Ahmadi P, Salehi R, Mehravar M, Goharpey S. Attentional demands of postural control during single leg stance in patients with anterior cruciate ligament reconstruction. Neurosci Lett. 2013;556:118–23. https://doi.org/10.1016/j.neulet.2013.10.022.
173. Yaru NC, Daniel DM, Penner D. The effect of tibial attachment site on graft impingement in an anterior cruciate ligament reconstruction. Am J Sports Med. 1992;20(2):217–20.
174. Romano VM, Graf BK, Keene JS, Lange RH. Anterior cruciate ligament reconstruction. The effect of tibial tunnel placement on range of motion. Am J Sports Med. 1993;21(3):415–8.
175. Shelbourne KD, Patel DV. Treatment of limited motion after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 1999;7(2):85–92.
176. Markolf KL, Hame S, Hunter DM, Oakes DA, Zoric B, Gause P, Finerman GA. Effects of femoral tunnel placement on knee laxity and forces in an anterior cruciate ligament graft. J Orthop Res. 2002;20(5):1016–24.

177. Simmons R, Howell SM, Hull ML. Effect of the angle of the femoral and tibial tunnels in the coronal plane and incremental excision of the posterior cruciate ligament on tension of an anterior cruciate ligament graft: an in vitro study. J Bone Joint Surg. 2003;85-A(6):1018–29.
178. Fu FH, Bennett CH, Ma CB, Menetrey J, Lattermann C. Current trends in anterior cruciate ligament reconstruction. Part II. Operative procedures and clinical correlations. Am J Sports Med. 2000;28(1):124–30.
179. Jackson DW, Schaefer RK. Cyclops syndrome: loss of extension following intraarticular anterior cruciate ligament reconstruction. Arthroscopy. 1990;6(3):171–8.
180. Petsche TS, Hutchinson MR. Loss of extension after reconstruction of the anterior cruciate ligament. J Am Acad Orthop Surg. 1999;7(2):119–27.
181. Millett PJ, Wickiewicz TL, Warren RF. Motion loss after ligament injuries to the knee. Part I: causes. Am J Sports Med. 2001;29(5):664–75.
182. Austin JC, Phornphutkul C, Wojtys EM. Loss of knee extension after anterior cruciate ligament reconstruction: effects of knee position and graft tensioning. J Bone Joint Surg. 2007;89(7):1565–74.
183. Noyes FR, Barber-Westin SD. Prevention and treatment of knee arthrofibrosis. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 1059–102. https://doi.org/10.1016/b978-0-323-32903-3.00038-x.
184. Mauro CS, Irrgang JJ, Williams BA, Harner CD. Loss of extension following anterior cruciate ligament reconstruction: analysis of incidence and etiology using IKDC criteria. Arthroscopy. 2008;24(2):146–53. https://doi.org/10.1016/j.arthro.2007.08.026.
185. Shelbourne KD, Johnson GE. Outpatient surgical management of arthrofibrosis after anterior cruciate ligament surgery. Am J Sports Med. 1994;22(2):192–7.
186. Shelbourne KD, Wilckens JH, Mollabashy A, DeCarlo M. Arthrofibrosis in acute anterior cruciate ligament reconstruction. The effect of timing of reconstruction and rehabilitation. Am J Sports Med. 1991;19(4):332–6.
187. Strum GM, Friedman MJ, Fox JM, Ferkel RD, Dorey FH, Del Pizzo W, Snyder SJ. Acute anterior cruciate ligament reconstruction. Analysis of complications. Clin Orthop Relat Res. 1990;253:184–9.
188. Wasilewski SA, Covall DJ, Cohen S. Effect of surgical timing on recovery and associated injuries after anterior cruciate ligament reconstruction. Am J Sports Med. 1993;21(3):338–42.
189. Mohtadi NG, Webster-Bogaert S, Fowler PJ. Limitation of motion following anterior cruciate ligament reconstruction. A case-control study. Am J Sports Med. 1991;19(6):620–4.
190. Shelbourne KD, Foulk DA. Timing of surgery in acute anterior cruciate ligament tears on the return of quadriceps muscle strength after reconstruction using an autogenous patellar tendon graft. Am J Sports Med. 1995;23(6):686–9.
191. Noyes FR, Barber-Westin SD. Diagnosis and treatment of complex regional pain syndrome. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 1122–60. https://doi.org/10.1016/b978-0-323-32903-3.00040-8.
192. Turner-Stokes L, Goebel A. Complex regional pain syndrome in adults: concise guidance. Clin Med. 2011;11(6):596–600.
193. Ogilvie-Harris DJ, Roscoe M. Reflex sympathetic dystrophy of the knee. J Bone Joint Surg. 1987;69(5):804–6.
194. Poehling GG, Pollock FE Jr, Koman LA. Reflex sympathetic dystrophy of the knee after sensory nerve injury. Arthroscopy. 1988;4(1):31–5.
195. Poplawski ZJ, Wiley AM, Murray JF. Post-traumatic dystrophy of the extremities. J Bone Joint Surg. 1983;65(5):642–55.
196. Jupiter JB, Seiler JG, Zienowicz R. Sympathetic maintained pain (causalgia) associated with a demonstrable peripheral-nerve lesion. Operative treatment. J Bone Joint Surg. 1994;76(9):1376–84.
197. Schwartzman RJ, Erwin KL, Alexander GM. The natural history of complex regional pain syndrome. Clin J Pain. 2009;25(4):273–80. https://doi.org/10.1097/AJP.0b013e31818ecea5.
198. Vaneker M, Wilder-Smith OH, Schrombges P, Oerlemans HM. Impairments as measured by ISS do not greatly change between one and eight years after CRPS 1 diagnosis. Eur J Pain. 2006;10(7):639–44. https://doi.org/10.1016/j.ejpain.2005.10.003.
199. de Mos M, Huygen FJ, van der Hoeven-Borgman M, Dieleman JP, Ch Stricker BH, Sturkenboom MC. Outcome of the complex regional pain syndrome. Clin J Pain. 2009;25(7):590–7. https://doi.org/10.1097/AJP.0b013e3181a11623.
200. Harden RN, Bruehl S, Stanton-Hicks M, Wilson PR. Proposed new diagnostic criteria for complex regional pain syndrome. Pain Med. 2007;8(4):326–31. https://doi.org/10.1111/j.1526-4637.2006.00169.x.
201. Harden RN, Bruehl S, Perez RS, Birklein F, Marinus J, Maihofner C, Lubenow T, Buvanendran A, Mackey S, Graciosa J, Mogilevski M, Ramsden C, Chont M, Vatine JJ. Validation of proposed diagnostic criteria (the "budapest criteria") for complex regional pain syndrome. Pain. 2010;150(2):268–74. https://doi.org/10.1016/j.pain.2010.04.030.
202. Maihofner C, Seifert F, Markovic K. Complex regional pain syndromes: new pathophysiological concepts and therapies. Eur J Neurol. 2010;17(5):649–60. https://doi.org/10.1111/j.1468-1331.2010.02947.x.
203. Oaklander AL, Fields HL. Is reflex sympathetic dystrophy/complex regional pain syndrome type I a small-fiber neuropathy? Ann Neurol. 2009;65(6):629–38. https://doi.org/10.1002/ana.21692.

204. Goebel A. Complex regional pain syndrome in adults. Rheumatology. 2011;50(10):1739–50. https://doi.org/10.1093/rheumatology/ker202.
205. de Mos M, Sturkenboom MC, Huygen FJ. Current understandings on complex regional pain syndrome. Pain Pract. 2009;9(2):86–99. https://doi.org/10.1111/j.1533-2500.2009.00262.x.
206. van Eijs F, Stanton-Hicks M, Van Zundert J, Faber CG, Lubenow TR, Mekhail N, van Kleef M, Huygen F. Evidence-based interventional pain medicine according to clinical diagnoses. 16. Complex regional pain syndrome. Pain Pract. 2011;11(1):70–87. https://doi.org/10.1111/j.1533-2500.2010.00388.x.
207. Beerthuizen A, van 't Spijker A, Huygen FJ, Klein J, de Wit R. Is there an association between psychological factors and the complex regional pain syndrome type 1 (CRPS1) in adults? A systematic review. Pain. 2009;145(1-2):52–9. https://doi.org/10.1016/j.pain.2009.05.003.
208. Schwenkreis P, Maier C, Tegenthoff M. Functional imaging of central nervous system involvement in complex regional pain syndrome. AJNR Am J Neuroradiol. 2009;30(7):1279–84. https://doi.org/10.3174/ajnr.A1630.
209. Dowd GS, Hussein R, Khanduja V, Ordman AJ. Complex regional pain syndrome with special emphasis on the knee. J Bone Joint Surg. 2007;89(3):285–90. https://doi.org/10.1302/0301-620X.89B3.18360.
210. Noyes FR, Barber-Westin SD. Posterolateral knee reconstruction with an anatomical bone-patellar tendon-bone reconstruction of the fibular collateral ligament. Am J Sports Med. 2007;35(2):259–73. https://doi.org/10.1177/0363546506293704.
211. Noyes FR, Barber-Westin S. Posterior cruciate ligament replacement with a two-strand quadriceps tendon-patellar bone autograft and a tibial inlay technique. J Bone Joint Surg. 2005;87(6):1241–52. https://doi.org/10.2106/JBJS.D.02272.
212. Heckmann TP, Barber-Westin SD, Noyes FR. Meniscal repair and transplantation: indications, techniques, rehabilitation, and clinical outcome. J Orthop Sports Phys Ther. 2006;36(10):795–814.

12 Early Postoperative Role of Blood Flow Restriction Therapy to Avoid Muscle Atrophy

Stephen D. Patterson, Luke Hughes, and Johnny Owens

12.1 Introduction

The anterior cruciate ligament (ACL) is the most frequently injured knee ligaments with over 120,000 injuries occurring annually in the United States [1]. The rehabilitation techniques used postoperatively have evolved over the last number of decades, from an approach of minimal muscle activity and full immobilisation [2] to one of increased muscle activation and range of movement (ROM) in the early stages following surgery [3–5]. A major consequence of ACL injury and surgery is skeletal muscle atrophy [6] and muscle weakness [7], which occurs postoperatively [8] and can remain for several years postoperatively [9]. The effects of muscle atrophy are unavoidable throughout the acute stages of ACL rehabilitation due to a period of reduced physical activity and muscular unloading to allow the new graft, bone tunnels and other issues concomitant with ACL injury and surgery to heal [10, 11]. Such issues may serve as contraindications to heavy-load exercise in load-compromised individuals. This is problematic as heavy exercise loads of 65–70% 1 repetition maximum (1RM) [12] are required to induce the tissue strain and physiological response required for an adaptive response [13]. Thus, clinicians are faced with the task of finding alternative rehabilitation tools, especially in the early stages of rehabilitation. One such tool that may play a role is blood flow restriction training (BFRT). This novel technique involves the application of a tourniquet at the proximal portion of the limb, which is then inflated either passively or during exercise, to maintain muscle mass or increase strength and hypertrophy, respectively. Throughout this chapter, we will outline the purpose of BFRT and the way it can be used in ACL rehabilitation.

12.2 Disuse Muscle Atrophy

Atrophy of skeletal muscle, manifested as loss of muscle mass [14], occurs in the postoperative recovery phase following ACL surgery. Substantial atrophy of the vastus lateralis muscle in particular has been observed [15], with significant atrophy evident following 5 days of muscular disuse [16]. Despite earlier ambulation, knee extensor (KE) muscle atrophy is still evident [17]. Significant decreases in thigh girth have been observed in the first 3–4 weeks post-surgery and can exceed a 20% loss of pre-surgery muscle size by 12 weeks [8]. Evidence has suggested that loss of thigh muscle size plays a larger role in strength deficits following ACL reconstruction

S. D. Patterson (✉) · L. Hughes
Faculty of Sport, Health and Applied Science, St Marys University, London, UK
e-mail: Stephen.Patterson@stmarys.ac.uk

J. Owens
Owens Recovery Science, INC, San Antonio, TX, USA

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_12

than neuromuscular deficits, and an emphasis on hypertrophy after surgery should be emphasised [18]. Furthermore, muscle atrophy may last much longer, as evidenced by deficits of 7% [19] and 3% [20] in total KE muscle volume in the injured limb compared to the contralateral limb at 12 and 18 months, respectively.

Atrophy is mainly evident in the injured limb and is due to intrinsic processes such as anabolic resistance. There is a decline in skeletal muscle myofibrillar muscle protein synthesis rate [21] and an increase in breakdown rate [22] during unloading due to a lack of muscle activation, which both likely contribute to changes in muscle protein balance and loss of muscle mass [14]. Short periods of disuse have been shown to lower myofibrillar protein synthesis rates and induce anabolic resistance to protein ingestion [23]. Other aspects such as reduced mitochondrial function, gene expression [24] and satellite cell proliferation [25] within the vastus lateralis are associated with muscle atrophy. Although these studies are not all specific to an ACL rehabilitation context, such findings demonstrate the rapid physiological changes within the unloaded limb that contribute to substantial atrophy, which is problematic during the early phases following ACL surgery [8]. Recently, a reduction in KE endurance has been demonstrated to be a likely predictor of postoperative atrophy in the first 4 weeks after ACL rehabilitation [26]. Although not fully understood, this may propose a role of reduced vascularity in the thigh postoperatively. If so, postoperative treatments to promote an angiogenic response may be warranted [26].

12.3 Impact on Strength

Research demonstrating muscle strength loss following ACL surgery is extensive. Though lower limb strength loss may involve multiple muscle groups, weakness of the KE and knee flexor (KF) muscle groups is most evident [27–29]. This is unsurprising given the involvement of these muscle groups in the dynamic control of the knee joint. Loss of KE and KF muscle strength in the injured limb appears universal across different types of surgical grafts [30–32]. Weakness of the KE muscle group in the injured limb is particularly substantial in the first 12 weeks following surgery, often exceeding a 30% loss of pre-surgery strength [26]. This results in limb strength asymmetries [33], which reports suggest range from 5 to 30% [6, 19, 27, 30, 34]. Loss of strength has also been observed in the non-injured limb [35, 36] with bilateral strength deficits ranging from 9 to 27% [30, 31, 34, 37]. Deficits in KF strength in the injured limb range from 9 to 27% [30, 31, 34, 37] similarly resulting in limb strength asymmetries [6]. Moreover, bilateral KF muscle strength deficits are observed [31]. Deficits in KE and KF muscle strength are not limited to the early phases following surgery. A 32.6% deficit in KE strength measured at 60°/s was observed in the injured limb compared to the contralateral limb at 6 months post-surgery [6]. KE and KF strength deficits have been observed up to 1 year [31, 32], 2 years [9], 3 years [31], 6 years [38] and 7 years [34] post-surgery. Unsurprisingly then, failure to tackle strength deficits in the early phases post-surgery is often considered a risk factor for longer-term deficits [20].

12.4 Arthrogenic Inhibition

Loss of strength may be of greater magnitude than the loss of muscle mass [39], and weakness following ACL surgery can be extensive [40, 41]. Therefore, atrophy alone may not account for the loss of muscle strength [29]. KE muscle weakness following ACL surgery may be due to a decrease in the recruitment of high threshold type II motor units, known as arthrogenic inhibition [42, 43]. Furthermore, anatomical changes of atrophy remain during early improvements in KE muscle strength following ACL surgery [17], suggesting that muscle weakness was partly attributable to a decrease in neural activation [44]. Indeed, bilateral KE muscle arthrogenic inhibition alongside muscle weakness has been observed 6 months post ACL surgery [7]. Following ACL surgery, arthrogenic inhibition is associated with joint damage, effusion and pain [45]. These factors alter the afferent signal sent to the central nervous system, which leads to an inhibitory signal transmitted to the KE muscle motor neuron pool and a decrease in voluntary muscle activity.

Following ACL surgery, patients may avoid contraction of the KE muscles when the knee is in full extension to prevent straining the graft. Reduction in KE group contraction may reduce anterior tibial subluxation [46], thus arthrogenic inhibition may be viewed as a compensatory mechanism to protect the knee joint from excessive anterior drawer [47]. It has been proposed that this compensatory mechanism may facilitate activation of the KF muscle group [46, 48] which may help reduce anterior forces and stabilise the knee joint in response to external varus and valgus load [49]. However, arthrogenic inhibition has also been observed in the KF muscles in a recent meta-analysis [46], which may partially explain deficits in KF strength following ACL surgery. Arthrogenic inhibition can persist at 12 months post-surgery [50], with reports of deficits of 15% or more remaining present 2 years post-surgery [35].

12.5 Blood Flow Restriction Training (BFRT) and Usage in ACL Rehabilitation

BFRT is a novel training method that aims to partially restrict arterial inflow and fully restrict venous outflow in active musculature during exercise [51]. The technique of restricting blood flow to the muscle using a pneumatic tourniquet system involves applying an external pressure, typically using a tourniquet cuff, to the most proximal aspect of the upper and lower limbs. When the cuff is inflated, there is gradual mechanical compression of the vasculature underneath the cuff, resulting in occluded venous return and partial restriction of arterial blood flow to structures distal to the cuff. Compression of the vasculature proximal to the muscle induces an ischemic environment, which subsequently results in hypoxia within the muscle [52]. Furthermore, the diminution of venous blood flow results in blood pooling within the capillaries of the occluded limbs, often reflected by visible muscle oedema. The level of such oedema, hypoxia and ischemia may be influenced by the amount of pressure applied. In addition to this, when performing exercise under conditions of restricted blood flow, during muscular contractions there is an increase in intramuscular pressure under the cuff [53], which further disturbs blood flow.

BFRT is applied during both voluntary resistance [54] and aerobic [55] exercise, and also passively without exercise [56, 57]. More recent research has examined the combination of BFRT with non-traditional exercise modalities, such as whole body vibration techniques [58] and neuromuscular electrical stimulation [59, 60]. At present, there is no universal standard method for the application of BFRT during exercise. Differences exist in the types of cuff used, pressures selection and the duration of BFRT application. Early research utilised more general procedures to determine cuff pressures, such as prescribing pressure relative to systolic blood pressure [61], thigh circumference [62], or arbitrary pressures. Recent research supports individualisation of BFRT application, where BFRT is prescribed as a percentage of arterial limb occlusion pressure (LOP), which represents the minimum pressure required for total arterial occlusion [51]. Additionally, the adoption of wider tapered tourniquet cuffs allows occlusion at lower pressures which may be more tolerable to the patient and reduce potentially dangerous pressure gradients [63].

BFRT may be used as a rehabilitation tool in ACL rehabilitation and periods of brief unloading and muscle disuse. Specifically, the low-load nature of BFRT may be critical in the early post-operative phase to increase quadriceps muscle strength, hypertrophy, endurance and voluntary activation. This is without heavy loading of the knee joint, thus allowing for preservation of the graft and reducing the risk of aggravating any concomitant cartilage, meniscal and bruising pathologies. Current, general BFRT research suggests it may be used in a progressive model through all stages of rehabilitation from early post-op to return to heavy-load exercise [64] and pre-injury activity levels. In the next section of this chapter, we will revisit this progressive model and discuss BFRT application specific to ACL rehabilitation throughout each phase. We will examine how BFRT may combat the mechanisms of muscle atrophy and strength loss previously discussed and update the model with more recent evidenced-based guidelines on safe and effective application. Table 12.1 provides an outline of the specific goals and suggested therapeutic exercises and modalities.

Table 12.1 Blood flow restriction training protocol following ACL surgery

Phase	Goals	Precautions	Suggested therapeutic exercise(s), modalities
1 preoperative (7 days to 4 weeks)	Create a protective effect for the surgical limb via multiple bouts of ischemic exercise (IPC)	As tolerated	BFRT: low-load, high volume of repetitions, longer reperfusion periods between exercises to enhance IPC and increase patient tolerance 80% LOP 4 sets (30, 15, 15, 15). 30 s rest between sets 1–3 min reperfusion between exercises Exercises at 15–30% 1RM: leg press (single leg), knee extension, seated hamstring curl, standing plantar flexion
	Increase muscle strength and endurance		
	Last session to be performed within 48 h of surgery to emphasise protective window of IPC		
Immediately postoperative (days 0–3)	Control pain, inflammation, effusion	Monitor swelling and pain	Passive joint and soft tissue mobilisation
			Flexibility training (avoid hamstring stretch with hamstring graft)
			Gentle active ROM
	Maintain ROM		SLR, hip abduction/adduction (avoid extensor lag with SLR flexion)
	Restore voluntary muscle contraction		Begin weight shifting and proprioception training
	Partial to full weight bearing as tolerated		WBAT with crutches until quadriceps control gained
	Restore patellar mobility		Cryotherapy as needed
Phase 2 (days 3–7)	Control pain, inflammation, effusion	Monitor swelling and pain BFRT as long as no signs for VTE or improper wound healing	Continue passive joint and soft tissue mobilisations
			Progress flexibility training
	ROM 0–110°		Initiate passive BFRT (5 min at 100% LOP/5 mins reperfusion × 4)
	Improve muscle strength and endurance		Or initiate passive MFRT with NMES (10–20% MVC) E-stimulation cuff placed proximal on limb (80% LOP)
	Progress WBAT		Balance and proprioceptive training
	Restore full patellar mobility		Cryotherapy as needed
Phase 3 (1–3 weeks)	ROM 0–125°	Monitor swelling and pain. BFRT as long as no signs for VTE or improper wound healing	Continue progression with active ROM and flexibility
	Eliminate pain, inflammation, effusion		Continue BFRT with NMES (10–20% MVC, 80% LOP)
	Improve muscle strength and endurance		Begin stationary bike (if 105° flexion present) with BFRT (80% LOP): level 2 or 3 on bike (easy) for 15–20 min
	Restore proprioception		Proprioceptive, neuromuscular, stability training
	Discharge crutches as tolerated		Cryotherapy as needed

Table 12.1 (continued)

Phase	Goals	Precautions	Suggested therapeutic exercise(s), modalities
Phase 4 (3–12 weeks)	Restore full ROM 0–135°		Continue progression with active ROM and flexibility
	Increase lower extremity strength and endurance Improve dynamic balance and proprioception		BFRT (4 sets: 30, 15, 15, 15; 80% LOP): Leg press (bilateral or single leg), step-back lunge, knee extension, hamstring curl, plantar flexion, bike (15–20 min active work, 80% LOP), increase intensity
	Improve neuromuscular control		Proprioceptive, neuromuscular, stability training
	Restore functional capability and confidence		Cryotherapy as needed
Phase 5 (>12 weeks)	Increase work capacity Increase tendon loading		Phase out BFRT (4 sets: 30, 15, 15, 15; 80% LOP) to 1–2 ×/week until full transition to heavy-load strength training
	Increase rate of force development		Begin heavy-load strength training (>75% 1RM; 3–4 sets × 4–12 reps) intermittently with BFRT until no need for further BFRT: Unilateral exercises, multiple planes
	Increase ability to withstand force in multiple planes of movement		Bilateral/unilateral multi- and single plane plyometrics
	Develop landing tasks		Proprioceptive, neuromuscular, stability training

BFRT blood flow resistance training, *IPC* ischemic preconditioning, *LOP* limb occlusion pressure, *NMES* neuromuscular electrical stimulation, *MVC* maximum voluntary contraction, *RM* repetition maximum, *ROM* range of motion, *SLR* straight leg raises, *WBAT* weight bearing as tolerated

This is an empirical rehabilitation protocol that describes best practice with BFR and how it can be implemented for ACLR.

12.5.1 Phase 1: Prehabilitation with BFRT

Recent evidence suggests pathophysiological changes not only intra-articularly after ACL surgery but also within the thigh muscle. After injury, but prior to surgery, muscle pennation angle and satellite cell content is reduced and extracellular matrix content is increased [65]. These changes within the muscle were also found to persist despite ACL surgery and extensive rehabilitation [65]. The preoperative window may allow for adaptive changes in the acute stages of injury where the limb can tolerate low loads under BFRT that would not be tolerated immediately postoperatively. Three weeks of BFRT has demonstrated a significant increase in both type I and II muscle fibre satellite cell content and significant gains in muscle fibre size and strength in the quadriceps. Theoretically, this 3-week application preoperatively could serve as a countermeasure to the pathophysiological changes after ACL surgery. Additionally, the level of quadriceps muscle endurance not strength has been found to be the strongest predictor of muscle wasting the first month postoperatively [26]. This may require clinicians to look for treatment approaches to not only address the muscle but the supporting vasculature that may be compromised from ischemic-reperfusion injury during surgery. Seven days of passive BFRT, tourniquet inflation without exercise, demonstrated improved muscle oxidative capacity via enhanced mitochondrial and vascular function in healthy individuals [66]. Furthermore, application of BFRT 8 days prior to ACL surgery resulted in no loss of quadriceps muscle endurance at 4 weeks post-operation compared to a 50% loss in work matched controls [26]. From this, it can be suggested that the application of BFRT 1 to 2 weeks preoperatively, with a focus on low-load exercises for the thigh muscle, may help counteract acute pathophysiological muscle changes associated with ACL reconstruction.

12.5.2 Phase 2: Early Postoperative with BFRT

The primary goals of the early postoperative phase are reducing joint effusion, pain control and combating muscle atrophy and strength loss. As previously mentioned, muscle atrophy during early postoperative unloading [14] is caused by a disturbance in muscle protein balance, namely a decrease in synthesis [67] and an increase in breakdown [22]. A modest amount of research has examined the use of passive BFRT. The use of passive BFRT is typically applied with a protocol consisting of 5 sets comprised of 5 min of full occlusion followed by 3 min of reperfusion. Takarada et al. demonstrated that this protocol could attenuate post-surgery atrophy of the KE and KF muscles in patients by approximately 50% compared to controls when used for 10 days, beginning at 4 days post-surgery [68]. Following a period of unloading in healthy individuals, passive BFRT was also found to compare more favourably to control and isometric exercise conditions at attenuating atrophy [69], even at a low pressure of 50 mmHg [57]. However, not all evidence is positive for this technique; one study found no attenuation of muscle atrophy following BFRT compared to a control group in ACL reconstructed patients 2 weeks post-surgery [70]. A definitive mechanism behind such adaptations to BFRT per se, despite the absence of mechanical tension, has not been identified yet. Passive BFRT is thought to cause cell swelling that is evident after release of the cuff [71]; such acute cell swelling can stimulate protein synthesis and suppress breakdown [72] which may explain the attenuation of atrophy with BFRT [68, 69]. Enhanced mTOR signalling in a rat skeletal muscle model has also been demonstrated with passive BFRT [73].

The use of passive BFRT offers further benefits in the early stages post-surgery. Postoperative pain has an inflammatory and nociceptive nature that results. It from the interaction between tissue damage and nociceptive sensory receptor stimulation through inflammatory mediators. Passive BFRT, also known as ischemic pre-conditioning (IPC), has been shown to reduce postoperative pain in patients undergoing conventional cholecystectomy who were submitted to remote preconditioning ischemic before the surgical procedure [70]. Furthermore, passive BFRT has been shown to reduce pain following exercise-induced muscle damage, which may in part be related to reduced swelling [74, 75]. Therefore, though not directly studied following ACL surgery, passive BFRT may be a useful aid in reducing swelling and pain in the early stages post-surgery.

Neuromuscular electrical stimulation (NMES) is commonly used to combat muscle atrophy and strength loss following ACL surgery [28] and can prevent the decrease in muscle protein synthesis during unloading [76]. Whilst there is some evidence that NMES alone can help prevent skeletal muscle atrophy following periods of disuse, the evidence for strength maintenance is not as clear [76]. Recently, studies combining low-intensity NMES with BFRT have found increases in muscle size and strength [59, 60] and thus may be an adjunct to BFRT in the early stages post-surgery. NMES of the quadriceps does not involve transmission of large forces through the tibiofemoral joint, thus exhibiting a low risk of damaging the graft or exacerbating any cartilage, meniscal, or bone injuries. Early increases in muscle strength and size are necessary to perform voluntary training later in the rehabilitation process [77], and there is debate over whether passive BFRT alone is truly effective [70]. Thus, we suggest NMES with BFRT as an updated and potentially more effective approach to the early postoperative phase.

12.5.3 Phase 3: Postoperative Ambulation with BFRT

The primary goals of this phase are to further attenuate atrophy and strength loss, improve quadriceps activation and control and normalise gait kinematics. Full knee extension is required to start gait re-education [78]; if a patient starts to undertake high volumes of walking with a pathological gait pattern, there is opportunity for further injury or tissue overload of other structures supporting that movement pattern [79]. In order to provide patients with full ROM: BFRT walking activities can help meet the goals of this phase.

Unloaded isotonic work acts as a prerequisite for regaining muscle strength and size during low-load resistance rehabilitation. Combining activities such as walking with BFRT has been shown to increase muscle size and strength [55] and multiple aspects of physical function [80]; it may therefore be used to increase muscle size and strength in early ambulation post-ACL surgery. Once patients are able, cycling can also be combined with BFRT; low-intensity cycling with BFRT can concurrently increase muscle hypertrophy and aerobic capacity [81]. It may also promote muscle deoxygenation and metabolic strain, thus further stimulating endurance adaptations in the quadriceps to combat the post-surgery loss of muscular endurance [82]. BFRT should be prescribed at a pressure between 60% and 80% LOP; aerobic exercise intensity is typically prescribed at a percentage of <50% VO2max, depending upon on the mode of exercise. However, this is difficult to reproduce clinically, and anecdotal observations support the use of simple low-level cycling, such as level 2 or 3 on an exercise bike, whilst under BFRT produce a significant aerobic workload.

12.5.4 Phase 4: Low-Load Resistance Training with BFRT

Once patients have full range knee flexion and extension and gait is normalised, low-load resistance training is normally introduced. This is to accelerate the hypertrophy process and improve strength to begin a return to full weight bearing and pre-injury activity levels. The strength and hypertrophy adaptations from low-load resistance training with BFRT are well-documented, with our recent review and meta-analysis concluding that low-load BFRT is an effective, tolerable and useful clinical musculoskeletal rehabilitation tool [83]. During this phase of the model, progressive and individualised low-load resistance training on 2 to 3 day/week using a low-load between 20% and 30% 1RM is sufficient for muscle size and strength adaptations [51, 84] using an occlusive pressure of 60–80% LOP [85].

Low-load resistance training with BFRT has been shown to increase muscle protein synthesis, which may be a result of activation of the mTOR signalling pathway that is thought to be an important cellular mechanism for enhanced muscle protein synthesis with BFRT exercise [86]. Such increases in muscle protein synthesis with low-loads can help recover and increase muscle size without loading the tibiofemoral joint with the heavy loads traditionally required for such an adaptation [87]. Low-load BFRT resistance exercise may also be used to combat the reduced muscle satellite cell abundance observed during periods of unloading following ACL surgery [25]. Proliferation of myogenic stem cells and addition of myonuclei to human skeletal muscle, accompanied by substantial myofibre hypertrophy, has been demonstrated following 23 training sessions in just under 3 weeks [88].

Regarding strength, the early preferential recruitment of type II fast-twitch fibres at low-loads due to the hypoxic muscular environment generated during BFRT is thought to be an important mechanism behind strength adaptations at such low loads [89]. Fast-twitch fibres, which are more susceptible to atrophy and activation deficits during unloading [90] and are normally only recruited at high intensities of muscular work, are recruited earlier. Indeed, several studies have demonstrated increased muscle activation during low-load BFRT resistance exercise [91, 92]. Greater internal activation intensity has been found relative to external load during low-load BFRT resistance exercise [93], suggesting type II fibres are preferentially recruited. Such preferential recruitment of the fibres that are more susceptible to atrophy [90] during the early stages of ACL rehabilitation may help combat activation problems whilst also triggering muscle hypertrophy and recovery of strength.

Interestingly, knee pain is reduced 24 h after an acute training session with BFRT following ACL surgery [94]. Recent evidence suggests BFRT may have an analgesic effect in patients with knee pain [95, 96]. The authors reported clinically significant immediate pain reduction in the physiotherapy session exercises following BFRT, whilst no pain reduction was observed in patients performing light-load training alone. Interestingly, the analgesia effect remained for 45 min following the physiotherapy session [95, 96]. Furthermore, Giles et al. demonstrated greater reduction in pain in activities of daily living with BFRT during an 8-week training period in patients with knee pain [97]. A reduction in knee joint pain due to both lower joint forces and a potential hypalgesia effect may be beneficial to patients following ACL surgery. Conditioned pain modulation resulting from cuff pressure and ischemic and exercise-induced muscle pain [98], exercise-related release of endogenous substances which inhibit nociceptive pathways [99] and hypoxia during BFRT may serve as mechanisms of hypalgesia with BFRT.

12.5.5 Phase 5: Heavy-Load Resistance Training with Low-Load BFRT

The end goal of ACL rehabilitation is for patients to be able to resume heavy loading and return to, or exceed, their pre-injury strength and activity levels. Heavy-load resistance training is more effective at increasing muscle strength compared to low-load BFRT [83], thus the latter may best be used as tool for effective and potentially quicker progression back to heavy exercise loads. Combination of low-intensity BFRT with heavy-load training has been shown to increase muscle strength and size gains observed in low-load BFRT alone [100]. Once physically able, individuals can integrate low-load BFRT with high-load resistance training to re-introduce larger mechanical loads to structures of the musculoskeletal system. This can stimulate other adaptations alongside muscle size and strength, such as tendon stiffness—which may not be possible with low-load BFRT [101]—to contribute to further improvements in physical function. It is important that the patient is physically able to utilise the heavy loads required without an adverse reaction. Therefore, it is recommended that the patient should be able to exercise with the loads required to stimulate muscle and tendon adaptation of 65–70% preoperative 1RM [87] when entering this advanced phase of rehabilitation.

12.6 Safety Considerations

Several published papers have questioned the safety of BFRT in different populations [53, 102–104]. Naturally, the safety issues have been reviewed in depth [105]. The following section discusses the reported side effects of BFRT, screening for risk minimisation and recommendations for safe practice in clinical research. For a detailed and most recent review on the safety of BFRT, the reader is directed to the work of Brander et al. [105]. They reported that no adverse responses to BFRT have been reported in RCTs involving clinical populations.

All clinical populations should be screened thoroughly and extensively to identify possible risks and contraindications prior to engagement in a BFRT rehabilitation program [105]. A number of screening tools have been published [53, 105] which are designed to examine intrinsic factors such as age, lifestyle factors and blood, respiratory and neurological disorders which may place an individual at greater risk of an adverse event during BFRT. Additionally, it is important that potential causes of rhabdomyolysis, such as infections and prolonged immobilisation, are ruled out before implementation of BFRT [106]. Using screening tools, thorough clinical judgement is required by a clinician alongside selection of the correct parameters of BFRT prescription by an individual who is knowledgeable in the optimal prescription and exercise responses to BFRT. Finally, it is important that the hemodynamic and physiological responses to light load BFRT are monitored during exercise and throughout a rehabilitation programme.

The risks of any adverse events seem minimal if patients are thoroughly screened prior to commencing a training programme and BFRT is prescribed, and subsequently applied, correctly. Moreover, there is no robust evidence to suggest that any risks are greater than traditional exercise modes such as heavy-load resistance training. At present, there are no complete standardised recommendations for use even in non-injured populations. However, optimal guidelines for parameters such as BFRT pressure and duration will help minimise any risk. This highlights the importance of an individualised approach to BFRT.

12.7 Conclusion

The rehabilitation process following surgery is complex and requires a number of different processes. Throughout this chapter, we describe the evidence behind the addition to BFRT in both prehabilitation and rehabilitation. The use of BFRT passively, in combination with NMES, aerobic exercise and resistance training, may all be used at various stages to enhance these processes. The application of BFRT is a safe and effective tool to optimise and offset skeletal muscle atrophy in the early stages post-surgery.

References

1. Gornitzky AL, Lott A, Yellin JL, Fabricant PD, Lawrence JT, Ganley TJ. Sport-specific yearly risk and incidence of anterior cruciate ligament tears in high school athletes: a systematic review and meta-analysis. Am J Sports Med. 2016;44:2716–23. https://doi.org/10.1177/0363546515617742.
2. Paulos L, Noyes FR, Grood E, Butler DL. Knee rehabilitation after anterior cruciate ligament reconstruction and repair. Am J Sports Med. 1981;9:140–9. https://doi.org/10.1177/036354658100900303.
3. Beynnon BD, Uh BS, Johnson RJ, Abate JA, Nichols CE, Fleming BC, Poole AR, Roos H. Rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind comparison of programs administered over 2 different time intervals. Am J Sports Med. 2005;33:347–59. https://doi.org/10.1177/0363546504268406.
4. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. J Orthop Sport Phys Ther. 2006;36:385–402. https://doi.org/10.2519/jospt.2006.2222.
5. Herrington L, Myer G, Horsley I. Task based rehabilitation protocol for elite athletes following anterior cruciate ligament reconstruction: a clinical commentary. Phys Ther Sport. 2013;14:188–98. https://doi.org/10.1016/j.ptsp.2013.08.001.
6. Thomas AC, Villwock M, Wojtys EM, Palmieri-Smith RM. Lower extremity muscle strength after anterior cruciate ligament injury and reconstruction. J Athl Train. 2013;48:610–20. https://doi.org/10.4085/1062-6050-48.3.23.
7. Thomas AC, Wojtys EM, Brandon C, Palmieri-Smith RM. Muscle atrophy contributes to quadriceps weakness after anterior cruciate ligament reconstruction. J Sci Med Sport. 2016;19:7–11. https://doi.org/10.1016/j.jsams.2014.12.009.
8. Grapar Žargi T, Drobnič M, Vauhnik R, Koder J, Kacin A. Factors predicting quadriceps femoris muscle atrophy during the first 12 weeks following anterior cruciate ligament reconstruction. Knee. 2016;24:319–28. https://doi.org/10.1016/j.knee.2016.11.003.
9. Kılınç BE, Kara A, Camur S, Oc Y, Celik H. Isokinetic dynamometer evaluation of the effects of early thigh diameter difference on thigh muscle strength in patients undergoing anterior cruciate ligament reconstruction with hamstring tendon graft. J Exerc Rehabil. 2015;11:95–100. https://doi.org/10.12965/jer.150100.
10. Davies GJ, McCarty E, Provencher M, Manske RC. ACL return to sport guidelines and criteria. Curr Rev Musculoskelet Med. 2017;10:307–14. https://doi.org/10.1007/s12178-017-9420-9.
11. McLean SG, Mallett KF, Arruda EM. Deconstructing the anterior cruciate ligament: what we know and do not know about function, material properties, and injury mechanics. J Biomech Eng. 2015;137:020906. https://doi.org/10.1115/1.4029278.
12. Folland JP, Williams AG. The adaptations to strength training: morphological and neurological contributions to increased strength. Sport Med. 2007;37:145–68. https://doi.org/10.2165/00007256-200737020-00004.
13. Spiering BA, Kraemer WJ, Vingren JL, Hatfield DL, Fragala MS, Ho JY, Maresh CM, Anderson JM, Volek JS. Responses of criterion variables to different supplemental doses of L-carnitine L-tartrate.

J Strength Cond Res. 2007;21:259–64. https://doi.org/10.1519/00124278-200702000-00046.
14. Atherton PJ, Greenhaff PL, Phillips SM, Bodine SC, Adams CM, Lang CH. Control of skeletal muscle atrophy in response to disuse: clinical/preclinical contentions and fallacies of evidence. Am J Physiol - Endocrinol Metab. 2016;311:594–604. https://doi.org/10.1152/ajpendo.00257.2016.
15. Häggmark T, Eriksson E. Cylinder or mobile cast brace after knee ligament surgery. Am J Sports Med. 1979;7:48–56. https://doi.org/10.1177/036354657900700111.
16. Wall BT, Dirks ML, Snijders T, Senden JMG, Dolmans J, Van Loon LJC. Substantial skeletal muscle loss occurs during only 5 days of disuse. Acta Physiol. 2014;210:600–11. https://doi.org/10.1111/apha.12190.
17. Norte GE, Knaus KR, Kuenze C, Handsfield GG, Meyer CH, Blemker SS, Hart JM. MRI-based assessment of lower extremity muscle volumes in patients before and after ACL reconstruction. J Sport Rehabil. 2017;32:1–40. https://doi.org/10.1123/jsr.2016-0141.
18. Fukunaga T, Johnson CD, Nicholas SJ, McHugh MP. Muscle hypotrophy, not inhibition, is responsible for quadriceps weakness during rehabilitation after anterior cruciate ligament reconstruction. Knee Surg Sport Traumatol Arthrosc. 2018;27:573–9. https://doi.org/10.1007/s00167-018-5166-1.
19. Konishi Y, Ikeda K, Nishino A, Sunaga M, Aihara Y, Fukubayashi T. Relationship between quadriceps femoris muscle volume and muscle torque after anterior cruciate ligament repair. Scand J Med Sci Sport. 2007;17:656–61. https://doi.org/10.1111/j.1600-0838.2006.00619.x.
20. Konishi Y, Kinugasa R, Oda T, Tsukazaki S, Fukubayashi T. Relationship between muscle volume and muscle torque of the hamstrings after anterior cruciate ligament lesion. Knee Surg Sport Traumatol Arthrosc. 2012;20:2270–4. https://doi.org/10.1007/s00167-012-1888-7.
21. de Boer MD, Selby A, Atherton P, Smith K, Seynnes OR, Maganaris CN, Maffulli N, Movin T, Narici MV, Rennie MJ. The temporal responses of protein synthesis, gene expression and cell signalling in human quadriceps muscle and patellar tendon to disuse. J Physiol. 2007;585:241–51. https://doi.org/10.1113/jphysiol.2007.142828.
22. Krawiec BJ, Frost RA, Vary TC, Jefferson LS, Lang CH. Hindlimb casting decreases muscle mass in part by proteasome-dependent proteolysis but independent of protein synthesis. Am J Physiol Metab. 2005;289:E969–80. https://doi.org/10.1152/ajpendo.00126.2005.
23. Wall BT, Dirks ML, Snijders T, van Dijk J-W, Fritisch M, Verdijk LB, van Loon LJC. Short-term muscle disuse lowers myofibrillar protein synthesis rates and induces anabolic resistance to protein ingestion. Am J Physiol Endocrinol Metab. 2015;310:E137–47. https://doi.org/10.1152/ajpendo.00227.2015.
24. Fox DK, Ebert SM, Bongers KS, Dyle MC, Bullard SA, Dierdorff JM, Kunkel SD, Adams CM. p53 and ATF4 mediate distinct and additive pathways to skeletal muscle atrophy during limb immobilization. AJP Endocrinol Metab. 2014;307:245–61. https://doi.org/10.1152/ajpendo.00010.2014.
25. Fry CS, Johnson DL, Ireland ML, Noehren B. ACL injury reduces satellite cell abundance and promotes fibrogenic cell expansion within skeletal muscle. J Orthop Res. 2017;35:1876–85. https://doi.org/10.1002/jor.23502.
26. Grapar Zargi T, Drobnic M, Jkoder J, Strazar K, Kacin A. The effects of preconditioning with ischemic exercise on quadriceps femoris muscle atrophy following anterior cruciate ligament reconstruction: a quasi-randomized controlled trial. Eur J Phys Rehabil Med. 2016;52:310–20.
27. Drechsler WI, Cramp MC, Scott OM. Changes in muscle strength and EMG median frequency after anterior cruciate ligament reconstruction. Eur J Appl Physiol. 2006;98:613–23. https://doi.org/10.1007/s00421-006-0311-9.
28. Palmieri-Smith RM, Thomas AC, Wojtys EM. Maximizing quadriceps strength after ACL reconstruction. Clin Sports Med. 2008;27:405–24. https://doi.org/10.1016/j.csm.2008.02.001.
29. Williams GN, Snyder-Mackler L, Barrance PJ, Buchanan TS. Quadriceps femoris muscle morphology and function after ACL injury: a differential response in copers versus non-copers. J Biomech. 2005;38:685–93. https://doi.org/10.1016/j.jbiomech.2004.04.004.
30. de Jong SN, van Caspel DR, van Haeff MJ, Saris DBFF. Functional assessment and muscle strength before and after reconstruction of chronic anterior cruciate ligament lesions. Arthrosc – J Arthrosc Relat Surg. 2007;23:21–8. https://doi.org/10.1016/j.arthro.2006.08.024.
31. Hiemstra LA, Webber S, MacDonald PB, Kriellaars DJ. Knee strength deficits after hamstring tendon and patellar tendon anterior cruciate ligament reconstruction. Med Sci Sports Exerc. 2000;32:1472–9. https://doi.org/10.1097/00005768-200008000-00016.
32. Kobayashi A, Higuchi H, Terauchi M, Kobayashi F, Kimura M, Takagishi K. Muscle performance after anterior cruciate ligament reconstruction. Int Orthop. 2004;28:48–51. https://doi.org/10.1007/s00264-003-0502-5.
33. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps Femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. J Orthop Sport Phys Ther. 2012;42:750–9. https://doi.org/10.2519/jospt.2012.4194.The.
34. Yasuda K, Ohkoshi Y, Tanabe Y, Kaneda K. Muscle weakness after anterior cruciate ligament reconstruction using patellar and quadriceps tendons. Bull Hosp Jt Dis Orthop Inst. 1991;51:175–85.
35. Urbach D, Nebelung W, Weiler HT, Awiszus F. Bilateral deficit of voluntary quadriceps mus-

cle activation after unilateral ACL tear. Med Sci Sports Exerc. 1999;31:1691–6. https://doi.org/10.1097/00005768-199912000-00001.
36. Urbach D, Awiszus F. Impaired ability of voluntary quadriceps activation bilaterally interferes with function testing after knee injuries. A twitch interpolation study. Int J Sports Med. 2002;23:231–6. https://doi.org/10.1055/s-2002-29074.
37. Konishi Y, Fukubayashi T. Relationship between muscle volume and muscle torque of the hamstrings after anterior cruciate ligament reconstruction. J Sci Med Sport. 2010;13:101–5. https://doi.org/10.1016/j.jsams.2008.08.001.
38. Keays SL, Bullock-Saxton JE, Keays AC, Newcombe PA, Bullock MI. A 6-year follow-up of the effect of graft site on strength, stability, range of motion, function, and joint degeneration after anterior cruciate ligament reconstruction: patellar tendon versus semitendinosus and gracilis tendon graft. Am J Sports Med. 2007;35:729–39. https://doi.org/10.1177/0363546506298277.
39. Jones SW, Hill RJ, Krasney PA, Conner BO, Peirce N, Greenhaff PL. Disuse atrophy and exercise rehabilitation in humans profoundly affects the expression of genes associated with the regulation of skeletal muscle mass. FASEB J. 2004;27:1–27. https://doi.org/10.1002/jcp.24604.Ribosome.
40. Chmielewski TL, Stackhouse S, Axe MJ, Snyder-Mackler L. A prospective analysis of incidence and severity of quadriceps inhibition in a consecutive sample of 100 patients with complete acute anterior cruciate ligament rupture. J Orthop Res. 2004;22:925–30. https://doi.org/10.1016/j.orthres.2004.01.007\rS0736026604000415.
41. Hurd W, Axe M, Snyder-Mackler L. A 10-year prospective trial of a patient management algorithm and screening examination for highly active individuals with ACL injury. Part I: outcomes. Am J Sport Med. 2010;36:40–7. https://doi.org/10.1177/0363546507308190.A.
42. Konishi Y, Fukubayashi T, Takeshita D. Mechanism of quadriceps femoris muscle weakness in patients with anterior cruciate ligament reconstruction. Scand J Med Sci Sport. 2002;12:371–5. https://doi.org/10.1249/01.mss.0000027628.04801.27.
43. Konishi Y, Konishi H, Fukubayashi T. Gamma loop dysfunction in quadriceps on the contralateral side in patients with ruptured ACL. Med Sci Sports Exerc. 2003;35:897–900. https://doi.org/10.1249/01.MSS.0000069754.07541.D2.
44. Lepley AS, Gribble PA, Thomas AC, Tevald MA, Sohn DH, Pietrosimone BG. Quadriceps neural alterations in anterior cruciate ligament reconstructed patients: a 6-month longitudinal investigation. Scand J Med Sci Sport. 2015;25:828–39. https://doi.org/10.1111/sms.12435.
45. Palmieri-Smith RM, Villwock M, Downie B, Hecht G, Zernicke R. Pain and effusion and quadriceps activation and strength. J Athl Train. 2013;48:186–91. https://doi.org/10.4085/1062-6050-48.2.10.
46. Kim HJ, Lee JH, Ahn SE, Park MJ, Lee DH. Influence of anterior cruciate ligament tear on thigh muscle strength and hamstring-to-quadriceps ratio: a meta-analysis. PLoS One. 2016;11:1–11. https://doi.org/10.1371/journal.pone.0146234.
47. Palmieri-Smith RM, Thomas AC. A neuromuscular mechanism of posttraumatic osteoarthritis associated with ACL injury. Exerc Sport Sci Rev. 2009;37:147–53. https://doi.org/10.1097/JES.0b013e3181aa6669.
48. Georgoulis AD, Ristanis S, Moraiti CO, Paschos N, Zampeli F, Xergia S, Georgiou S, Patras K, Vasiliadis HS, Mitsionis G. ACL injury and reconstruction: clinical related in vivo biomechanics. Orthop Traumatol Surg Res. 2010;96:119–28. https://doi.org/10.1016/j.otsr.2010.09.004.
49. Hewett TE, Myer GD, Ford KR, Heidt RS, Colosimo AJ, McLean SG, Van Den Bogert AJ, Paterno MV, Succop P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med. 2005;33:492–501. https://doi.org/10.1177/0363546504269591.
50. Zebis MK, Andersen LL, Bencke J, Kjær M, Aagaard P. Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. Am J Sports Med. 2009;37:1967–73. https://doi.org/10.1177/0363546509335000.
51. Scott BR, Loenneke JP, Slattery KM, Dascombe BJ. Exercise with blood flow restriction: an updated evidence-based approach for enhanced muscular development. Sport Med. 2015;45:313–25. https://doi.org/10.1007/s40279-014-0288-1.
52. Manini TM, Clark BC. Blood flow restricted exercise and skeletal muscle health. Exerc Sport Sci Rev. 2009;37:78–85. https://doi.org/10.1097/JES.0b013e31819c2e5c.
53. Kacin A, Žargi TG, Rosenblatt B, Biswas A. Safety considerations with blood flow restricted resistance training. Ann Kinesiol. 2015;6:3–26.
54. Fahs CA, Loenneke JP, Rossow LM, Tiebaud RS, Bemben MG. Methodological considerations for blood flow restricted resistance exercise. J Trainology. 2012;1:14–22. https://doi.org/10.17338/trainology.1.1_14.
55. Abe T, Kearns CF, Sato Y. Muscle size and strength are increased following walk training with restricted venous blood flow from the leg muscle, Kaatsu-walk training. J Appl Physiol. 2006;100:1460–6. https://doi.org/10.1152/japplphysiol.01267.2005.
56. Cook SB, Brown KA, DeRuisseau K, Kanaley JA, Ploutz-Snyder LL. Skeletal muscle adaptations following blood flow-restricted training during 30 days of muscular unloading. J Appl Physiol. 2010;109:341–9. https://doi.org/10.1152/japplphysiol.01288.2009.
57. Kubota A, Sakuraba K, Koh S, Ogura Y, Tamura Y. Blood flow restriction by low compressive force prevents disuse muscular weakness. J Sci Med Sport. 2011;14:95–9. https://doi.org/10.1016/j.jsams.2010.08.007.

58. Miller RM, Keeter VM, Freitas EDS, Heishman AD, Knehans AW, Bemben DA, Bemben MG. Effects of blood flow restriction combined with post-activation potentiation stimuli on jump performance in recreationally active males. J Strength Cond Res. 2017:1. https://doi.org/10.1519/JSC.0000000000002110.
59. Gorgey AS, Timmons MK, Dolbow DR, Bengel J, Fugate-Laus KC, Michener LA, Gater DR. Electrical stimulation and blood flow restriction increase wrist extensor cross-sectional area and flow meditated dilatation following spinal cord injury. Eur J Appl Physiol. 2016;116:1231–44. https://doi.org/10.1007/s00421-016-3385-z.
60. Natsume T, Ozaki H, Saito AI, Abe T, Naito H. Effects of Electrostimulation with blood flow restriction on muscle size and strength. Med Sci Sports Exerc. 2015;47:2621–7. https://doi.org/10.1249/MSS.0000000000000722.
61. Takano H, Morita T, Iida H, Asada KI, Kato M, Uno K, Hirose K, Matsumoto A, Takenaka K, Hirata Y, Eto F, Nagai R, Sato Y, Nakajima T. Hemodynamic and hormonal responses to a short-term low-intensity resistance exercise with the reduction of muscle blood flow. Eur J Appl Physiol. 2005;95:65–73. https://doi.org/10.1007/s00421-005-1389-1.
62. Loenneke JP, Allen KM, Mouser JG, Thiebaud RS, Kim D, Abe T, Bemben MG. Blood flow restriction in the upper and lower limbs is predicted by limb circumference and systolic blood pressure. Eur J Appl Physiol. 2014;115:397–405. https://doi.org/10.1007/s00421-014-3030-7.
63. Noordin S, McEwen JA, Kragh JF, Eisen A, Masri BA. Surgical tourniquets in orthopaedics. J Bone Jt Surg Ser A. 2009;91:2958–67. https://doi.org/10.2106/JBJS.I.00634.
64. Loenneke JP, Abe T, Wilson J, Thiebaud R, Fahs C, Rossow L, Bemben M. Blood flow restriction: an evidence based progressive model (review). Acta Physiol Hung. 2012;99:235–50. https://doi.org/10.1556/APhysiol.99.2012.3.1.
65. Noehren B, Andersen A, Hardy P, Johnson DL, Ireland ML, Thompson KL, Damon B. Cellular and morphological alterations in the Vastus Lateralis muscle as the result of ACL injury and reconstruction Brian. J Bone Jt Surg. 2016;98:1541–7. https://doi.org/10.1016/B978-0-323-29755-4.00037-3.
66. Jeffries O, Waldron M, Pattison JR, Patterson SD. Enhanced local skeletal muscle oxidative capacity and microvascular blood flow following 7-day ischemic preconditioning in healthy humans. Front Physiol. 2018;9:1–12. https://doi.org/10.3389/fphys.2018.00463.
67. de Boer MD, Seynnes OR, di Prampero PE, Pišot R, Mekjavić IB, Biolo G, Narici MV. Effect of 5 weeks horizontal bed rest on human muscle thickness and architecture of weight bearing and non-weight bearing muscles. Eur J Appl Physiol. 2008;104:401–7. https://doi.org/10.1007/s00421-008-0703-0.
68. Takarada Y, Takazawa H, Ishii N. Applications of vascular occlusion diminish disuse atrophy of knee extensor muscles. Med Sci Sports Exerc. 2000;32:2035–9. https://doi.org/10.1097/00005768-200012000-00011.
69. Kubota A, Sakuraba K, Sawaki K, Sumide T, Tamura Y. Prevention of disuse muscular weakness by restriction of blood flow. Med Sci Sports Exerc. 2008;40:529–34. https://doi.org/10.1249/MSS.0b013e31815ddac6.
70. Iversen E, Røstad V, Larmo A. Intermittent blood flow restriction does not reduce atrophy following anterior cruciate ligament reconstruction. J Sport Heal Sci. 2016;5:115–8. https://doi.org/10.1016/j.jshs.2014.12.005.
71. Loenneke JP, Fahs CA, Rossow LM, Abe T, Bemben MG. The anabolic benefits of venous blood flow restriction training may be induced by muscle cell swelling. Med Hypotheses. 2012;78:151–4. https://doi.org/10.1016/j.mehy.2011.10.014.
72. Berneis K, Ninnis R, Häussinger D, Keller U. Effects of hyper- and hypoosmolality on whole body protein and glucose kinetics in humans. Am J Phys. 1999;276:E188–95.
73. Nakajima T, Yasuda T, Koide S, Yamasoba T, Obi S, Toyoda S, Sato Y, Inoue T, Kano Y. Repetitive restriction of muscle blood flow enhances mTOR signaling pathways in a rat model. Heart Vessel. 2016;31:1685–95. https://doi.org/10.1007/s00380-016-0801-6.
74. Franz A, Behringer M, Nosaka K, Buhren BA, Schrumpf H, Mayer C, Zilkens C, Schumann M. Mechanisms underpinning protection against eccentric exercise-induced muscle damage by ischemic preconditioning. Med Hypotheses. 2017;98:21–7. https://doi.org/10.1016/j.mehy.2016.11.008.
75. Page W, Swan R, Patterson SD. The effect of intermittent lower limb occlusion on recovery following exercise-induced muscle damage: a randomized controlled trial. J Sci Med Sport. 2017;20:729–33. https://doi.org/10.1016/j.jsams.2016.11.015.
76. Dirks ML, Wall BT, Snijders T, Ottenbros CLP, Verdijk LB, Van Loon LJC. Neuromuscular electrical stimulation prevents muscle disuse atrophy during leg immobilization in humans. Acta Physiol. 2014;210:628–41. https://doi.org/10.1111/apha.12200.
77. Feil S, Newell J, Minogue C, Paessler HH. The effectiveness of supplementing a standard rehabilitation program with superimposed neuromuscular electrical stimulation after anterior cruciate ligament reconstruction: a prospective, randomized, single-blind study. Am J Sports Med. 2011;39:1238–47. https://doi.org/10.1177/0363546510396180.
78. Manske RC, Prohaska D, Lucas B. Recent advances following anterior cruciate ligament reconstruction: rehabilitation perspectives - critical reviews in rehabilitation medicine. Curr Rev Musculoskelet Med. 2012;5:59–71. https://doi.org/10.1007/s12178-011-9109-4.
79. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Huang B, Hewett TE. Biomechanical measures

during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. Am J Sports Med. 2010;38:1968–78. https://doi.org/10.1177/0363546510376053.

80. Clarkson MJ, Conway L, Warmington SA. Blood flow restriction walking and physical function in older adults: a randomized control trial. J Sci Med Sport. 2017;20:1041–6. https://doi.org/10.1016/j.jsams.2017.04.012.
81. Abe T, Fujita S, Nakajima T, Sakamaki M, Ozaki H, Ogasawara R, Sugaya M, Kudo M, Kurano M, Yasuda T, Sato Y, Ohshima H, Mukai C, Ishii N. Effects of low-intensity cycle training with restricted leg blood flow on thigh muscle volume and VO2 max in young men. J Sport Sci Med. 2010;9:452–8. https://doi.org/10.1097/JPT.0b013e3181d07a73.
82. Corvino RB, Rossiter HB, Loch T, Martins JC, Caputo F. Physiological responses to interval endurance exercise at different levels of blood flow restriction. Eur J Appl Physiol. 2017;117:39–52. https://doi.org/10.1007/s00421-016-3497-5.
83. Hughes L, Paton B, Rosenblatt B, Gissane C, Patterson SD. Blood flow restriction training in clinical musculoskeletal rehabilitation: a systematic review and meta-analysis. Br J Sports Med. 2017;51:1003–11. https://doi.org/10.1136/bjsports-2016-097071.
84. Wernbom M, Augustsson J, Raastad T. Ischemic strength training: a low-load alternative to heavy resistance exercise? Scand J Med Sci Sport. 2008;18:401–16. https://doi.org/10.1111/j.1600-0838.2008.00788.x.
85. Patterson SD, Hughes L, Head P, Warmington S, Brandner C. Blood flow restriction training: a novel approach to augment clinical rehabilitation: how to do it. Br J Sports Med. 2017;51:1648–9. https://doi.org/10.1136/bjsports-2017-097738.
86. Gundermann DM, Walker DK, Reidy PT, Borack MS, Dickinson JM, Volpi E, Rasmussen BB. Activation of mTORC1 signaling and protein synthesis in human muscle following blood flow restriction exercise is inhibited by rapamycin. AJP Endocrinol Metab. 2014;306:E1198–204. https://doi.org/10.1152/ajpendo.00600.2013.
87. Garber CE, Blissmer B, Deschenes MR, Franklin BA, Lamonte MJ, Lee IM, Nieman DC, Swain DP. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. Med Sci Sports Exerc. 2011;43:1334–59. https://doi.org/10.1249/MSS.0b013e318213fefb.
88. Nielsen JL, Aagaard P, Bech RD, Nygaard T, Hvid LG, Wernbom M, Suetta C, Frandsen U. Proliferation of myogenic stem cells in human skeletal muscle in response to low-load resistance training with blood flow restriction. J Physiol. 2012;590:4351–61. https://doi.org/10.1113/jphysiol.2012.237008.
89. Pearson SJ, Hussain SR. A review on the mechanisms of blood-flow restriction resistance training-induced muscle hypertrophy. Sport Med. 2015;45:187–200.
90. Wang Y, Pessin JE. Mechanisms for fiber-type specificity of skeletal muscle atrophy. Curr Opin Clin Nutr Metab Care. 2013;16:243–50. https://doi.org/10.1097/MCO.0b013e328360272d.
91. Fatela P, Reis JF, Mendonca GV, Avela J, Mil-Homens P. Acute effects of exercise under different levels of blood-flow restriction on muscle activation and fatigue. Eur J Appl Physiol. 2016;116:985–95. https://doi.org/10.1007/s00421-016-3359-1.
92. Lauver JD, Cayot TE, Rotarius T, Scheuermann BW. The effect of eccentric exercise with blood flow restriction on neuromuscular activation, microvascular oxygenation, and the repeated bout effect. Eur J Appl Physiol. 2017;117:1005–15. https://doi.org/10.1007/s00421-017-3589-x.
93. Yasuda T, Brechue W, Fujita T, Shirakawa J, Sato Y, Abe T. Muscle activation during low-intensity muscle contractions with restricted blood flow. J Sports Sci. 2009;27:479–89. https://doi.org/10.1080/02640410802626567.
94. Hughes L, Paton B, Haddad F, Rosenblatt B, Gissane C, Patterson SD. Comparison of the acute perceptual and blood pressure response to heavy load and light load blood flow restriction resistance exercise in anterior cruciate ligament reconstruction patients and non-injured populations. Phys Ther Sport. 2018;33:54–61.. https://doi.org/10.1016/j.ptsp.2018.07.002
95. Korakakis V, Whiteley R, Epameinontidis K. Blood flow restriction induces hypoalgesia in recreationally active adult male anterior knee pain patients allowing therapeutic exercise loading. Phys Ther Sport. 2018;32:235–43. https://doi.org/10.1016/j.ptsp.2018.05.021.
96. Korakakis V, Whiteley R, Giakas G. Low load resistance training with blood flow restriction decreases anterior knee pain more than resistance training alone. A pilot randomised controlled trial. Phys Ther Sport. 2018;34:121–8. https://doi.org/10.1016/j.ptsp.2018.09.007.
97. Giles L, Webster KE, Mcclelland J, Cook JL. Quadriceps strengthening with and without blood flow restriction in the treatment of patellofemoral pain: a double-blind randomised trial. Br J Sports Med. 2017;51:1688–94. https://doi.org/10.1136/bjsports-2016-096329.
98. Tuveson B, Leffler AS, Hansson P. Time dependant differences in pain sensitivity during unilateral ischemic pain provocation in healthy volunteers. Eur J Pain. 2006;10:225–32. https://doi.org/10.1016/j.ejpain.2005.03.010.
99. Koltyn KF, Brellenthin AG, Cook DB, Sehgal N, Hillard C. Mechanisms of exercise-induced Hypoalgesia. J Pain. 2014;15:1294–304. https://doi.org/10.1016/j.jpain.2014.09.006.Mechanisms.

100. Yasuda T, Ogasawara R, Sakamaki M, Ozaki H, Sato Y, Abe T. Combined effects of low-intensity blood flow restriction training and high-intensity resistance training on muscle strength and size. Eur J Appl Physiol. 2011;111:2525–33. https://doi.org/10.1007/s00421-011-1873-8.
101. Kubo K, Komuro T, Ishiguro N, Tsunoda N, Sato Y, Ishii N, Kanehisa H, Fukunaga T, Kubo K, Komuro T, Ishiguro N, Tsunoda N, Sato Y, Ishii N, Kanehisa H, Fukunaga T. Effect of low-load resistance training with vascular occlusion on the mechanical properties of muscle and tendon. J Appl Biomech. 2006;22:112–9. https://doi.org/10.1123/jab.22.2.112.
102. Patterson SD, Brandner CR. The role of blood flow restriction training for applied practitioners: a questionnaire-based survey. J Sports Sci. 2017;36:123–30. https://doi.org/10.1080/02640414.2017.1284341.
103. Loenneke JP, Wilson JM, Wilson GJ, Pujol TJ, Bemben MG. Potential safety issues with blood flow restriction training. Scand J Med Sci Sport. 2011;21:510–8. https://doi.org/10.1111/j.1600-0838.2010.01290.x.
104. Wong ML, Formiga MF, Owens J, Asken T, Cahalin LP. Safety of blood flow restricted exercise in hypertension: a meta-analysis and systematic review with potential applications in orthopedic care. Tech Orthop. 2018;33:80–8.
105. Brandner CR, May AK, Clarkson MJ, Warmington SA. Reported side-effects and safety considerations for the use of blood flow restriction during exercise in practice and research. Tech Orthop. 2018;00:1–8. https://doi.org/10.1097/BTO.0000000000000259.
106. Allison RC, Bedsole DL. The other medical causes of rhabdomyolysis. Am J Med Sci. 2003;326:79–88. https://doi.org/10.1097/00000441-200308000-00005.

Part IV

Return to Sport Advanced Training Concepts

13 Current Concepts of Plyometric Exercises for the Lower Extremity

George J. Davies and Bryan L. Riemann

13.1 Introduction

Many sport activities require explosive movements of the lower extremities. Athletes are returning back to competition following knee injuries and surgeries faster than anyone could have predicted 10 years ago. However, that has not always been in the best interest of the patient because of reinjury rates and not being able to return to the same premorbid level of activity. The ability of the clinician to return the athlete back quickly and safely is multifactorial and includes advances in surgical techniques and rehabilitation, such as the use of integrated open and closed kinetic chain exercises, proprioceptive training, neuromuscular reactive dynamic stability exercises, and plyometrics.

In order to improve explosive power movements, plyometric exercises are incorporated into almost every program in the terminal phases of rehabilitation, strength, and conditioning or performance enhancement programs. To demonstrate the interest and popularity of plyometrics, a recent Google search for plyometrics identified over 3 million items. However, the scientific papers on plyometrics based on a PubMed Search (10/5/18) identified 183 articles. This includes 42 studies on the lower extremity and 36 studies on the knee, many of which demonstrate the effectiveness of plyometrics in improving power and performance in the lower extremities [1–11]. Evidence for the use of plyometric exercises in the lower extremities is available with regard to enhancement of performance in uninjured subjects [12–15] and also in those with injury or previous injury [16]. Numerous studies have described improvements in jump height [3, 6, 9, 17], sprint time [10, 18–20], running economy [18], and joint position sense and postural control as a result of plyometric training [8, 11, 21–26]. There is increasing evidence that lower extremity plyometric exercises and training may help prevent first time noncontact ACL injuries [1, 2, 27]. Several studies [8, 11, 19, 22–26, 28] have also reported that the introduction of a proper plyometric training program can increase neuromuscular control in all three planes of motion which will stress-shield the ACL and transfer it to the muscles, tendons, and bones. This allows for improved force dispersal, resulting in less torque applied directly to the knee [28].

G. J. Davies
Physical Therapy Program, Georgia Southern University - Armstrong Campus, Savannah, GA, USA

Biodynamics and Human Performance Center, Savannah, GA, USA
e-mail: gdavies@georgiasouthern.edu

B. L. Riemann (✉)
Biodynamics and Human Performance Center, Savannah, GA, USA

Department of Health Sciences and Kinesiology, Georgia Southern University - Armstrong Campus, Savannah, GA, USA
e-mail: briemann@georgiasouthern.edu

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_13

Because of the large forces involved, plyometrics are most appropriately used in the periodization program toward the terminal phases of rehabilitation. Moreover, this poses the question: why use plyometrics in the rehabilitation or performance enhancement of the athlete following a knee injury or surgery? Many functional moments of the lower extremity during running, jumping, and kicking use the plyometric concept as part of the functional movement patterns while executing the requirements for the sport. For example, when an athlete is preparing to jump, they use a countermovement which initiates the stretch-shortening cycle (SSC) that is one of the unique concepts of plyometric exercises. This countermovement provides a stretch to the muscle spindles and loads potential kinetic energy into the series and parallel elastic components of the muscle. This is then transferred to the shortening cycle and facilitates the resultant force production of the power phase, enhancing the performance pattern of the movement.

An important part of performance-based rehabilitation programs is the development of power often addressed by using plyometric exercises. Due to the concepts of specificity of rehabilitation and specific adaptation to imposed demands (SAID), plyometrics should form a foundation for the athlete to help build a power foundation from which to refine the skills of the sport. Every rehabilitation and conditioning program is designed to return the athlete back to his or her optimum function as quickly and as safely as possible. The rehabilitation and conditioning programs accomplish this with the use of exercises based on the functional and sports specificity principles. Plyometric exercises play an important role in this process with the athlete [29–44]. Consequently, it is important to understand the current concepts of plyometrics and how they can be integrated as advanced training concepts for the return to sport. Therefore, the purposes of this chapter are to discuss the history, definition, phases, scientific foundations and research, clinical guidelines, and contraindications of plymetric training. In addition, we will describe the design and components of plyometric programs, the theoretical training benefits, and specific plyometric exercises for the knee for rehabilitation and condition.

13.2 History of Plyometrics

Plyometrics were initially used for many decades in the original Russian and Eastern European countries in training track and field athletes [29–33, 45–51]. A popular and well-known track and field coach in Russia used the original plyometric concept, which he described as the shock method or jump training. It is thought that this type of training is the reason that, in the 1950s and 1960s, the Russian and European athletes were so successful in international competitions. The actual term *plyometrics* was first coined in 1975 by former Purdue University women's track coach, Fred Wilt [51]. Because of the definition, the purpose of plyometrics may be thought of as "to increase the measurement" which in sports performance is in testing or competition, such as throwing, sprinting, or jump height [16, 30–35, 45–47, 52].

13.3 Definition of Plyometrics

The term *plyometric* is a combination of two Greek words, plo and plythein. "Plio" means "more" or to increase, and "metric" means "to measure" [30–32, 47]. Plyometrics is an exercise technique that involves a blend of SSC and ballistic exercise modes. During the SSC phase, or the loading phase, a sudden stretch of the elastic components of the muscle-tendon unit and eccentric muscle activation occurs. The goal during this phase is to absorb and store the momentum of the limb(s), body, and any external loads (i.e., medicine ball) to bring the velocity to zero. Once the velocity is brought to zero, there is a brief period of time in which the muscle activity is best described as a transitory isometric period before there is an apparent concentric muscle activity. The unique feature of plyometrics is that the concentric phase, or rebound phase, involves the production of the body or external load into free space (ballistic mode).

13.4 Phases of Plyometrics

Although plyometrics have been described as consisting of two phases (eccentric and concentric), most clinicians consider plyometrics as triphasic by including the transition between the eccentric and concentric phases as the third phase. Plyometrics are a form of resistance training that involves a quick eccentric prestretch of the muscle, followed immediately by the resultant concentric muscle contraction. Most of the literature identifies plyometrics as having three phases of action: (1) eccentric prestretch loading phase, (2) transition, amortization, coupling, or rebound phase, and (3) concentric shortening power production performance phase [30, 34, 35, 46, 47].

13.4.1 Eccentric Prestretch Loading Phase

The eccentric prestretch phase has also been described as the countermovement, counterforce, facilitatory, preloading, presetting, preparatory, or readiness phase of the plyometric movement pattern [30, 34, 35, 53–58]. This phase begins with the application of a load; in the case of lower extremity plyometrics, such as drop jumps, the load often comes from contact with the ground. Through eccentric tension, the goal of this phase is to absorb the kinetic energy of the load and reverse the movement direction. Absorption of the energy occurs by stretching the muscle tendon units as a result of a load being applied. The prestretching prior to concentric muscle action is referred to as SSC [57].

The purpose of this phase is to stimulate the muscle receptors and activate the muscle spindle. Furthermore, this eccentric prestretch loads potential kinetic energy into the series elastic components (SEC) and parallel elastic components (PEC), which in turn contribute to the concentric force production. This stimulation of the muscle receptors is often referred to as the neurophysiological–biomechanical response [11, 21–24, 26, 59–62]. Several investigators [50, 53, 54, 63–67] have demonstrated that an eccentric muscle action immediately preceding a concentric muscle contraction will enhance the resultant concentric muscle contraction.

The advantages of SSC augmentation on the subsequent concentric phase have been well documented [57, 68], such as increased average velocity and power and higher peak force and acceleration. Interestingly, the exact mechanism of the augmentation remains uncertain [68, 69]. Current hypotheses include increased time for force development, strain energy storage in the series elastic muscle-tendon components, heightened levels of muscle activation, and evoking of stretch reflexes [64, 69–72]. A full examination of the research supporting each of these explanations is beyond the scope of this chapter; however, interested readers may refer to several papers dedicated to this topic [57, 68, 69, 72]. Important for the practitioner to understand is that SSC augmentation is related to the stretch magnitude, rate, and duration of the stretch [53, 57, 63, 69–71]. Thus, altering or changing any of these variables will have a potent effect on the amount of energy stored during the loading phase [73].

13.4.2 Transition, Amortization (Coupling, Rebound) Phase

This phase, also known as the electromechanical delay phase, is the time delay from the cessation of the eccentric prestretch phase to the onset of the concentric muscle contraction. This has also been described as moving from negative work to positive work [50, 64, 66, 74–77]. The amortization phase is the time delay between overcoming the negative work of the eccentric prestretch to generating the force production and accelerating the muscle contraction and the elastic recoil in the direction of the plyometric movement pattern [74, 75]. The shorter the amortization time, the more effective and powerful the plyometric movement is because the stored energy is used efficiently in the transition. Also, the shorter the amortization phase, the greater the work output is due to the maximal utilization of stored elastic energy [63]. If there is a delay in the amortization phase, the stored energy is wasted as heat, the stretch reflex is not activated, and the resultant contraction is not as effective. Decreasing the amortization phase is one of the key goals of plyometric training. We are performing studies at the Georgia Southern University Biodynamics and Human Performance Center to identify the optimum time of this phase to be most effective in facilitating performance.

Interspersed between the eccentric loading and concentric unloading phases is the transition phase. While this phase has also been referred to as the *coupling phase* [54, 78], traditionally, in the context of plyometrics, the length of time needed to transition between the loading phase and initiation of the concentric unloading phase has been referred to as *amortization time* [30, 32–35, 50, 51]. Paradoxically, amortization is defined as a decreasing attenuation, such as a home mortgage. Thus, because the unloading phase is augmented as a result of the preceding loading phase, we advocate referring to this phase as the *transition phase*. Similarly, instead of using amortization time, we prefer to use the term *time to rebound* to describe the length of time between the beginning of the loading and concentric unloading phases [34, 35].

Several investigations have described the muscle as being in an isometric contraction state as the shift from negative work to positive work occurs during this phase; thus, the increases in the muscle–tendon unit length are largely attributed to tendon elongation [54, 79, 80]. A shorter time to rebound has been demonstrated to produce a more enhanced concentric performance [54, 67, 70, 77]. For example, delaying the transition to the concentric unloading phase has been reported to reduce the augmentation of the SSC effect, as evidenced by higher oxygen consumption [67] and lower force and power–time curves [77]. One of the hypotheses concerning the diminished augmentation associated with a delayed time to rebound is that there is a reduction in the active actin–myosin cross-bridges, which reduces the tautness of the muscle-tendon unit and allows the strain energy stored in the tendon to be dissipated as heat [77]. One of the concerns of the eccentric action of the muscle is that it creates muscle damage and initially may create a short-term inhibition response to the muscle's performance [81–83].

13.4.3 Concentric Unloading Shortening Phase

The concentric shortening phase is often described as the power production, performance, facilitated, or enhancement phase of plyometrics [30, 32–35, 50, 51]. It has also been called the rebound and propulsion phase. This third component of SSC is the biomechanical response that utilizes the elastic properties of the prestretched muscles [24, 84, 85]. The phase begins with the muscle moving into a concentric muscle action and terminates with the projection of the load (e.g., body, medicine ball) into space. Again, assuming the transition from loading to unloading occurs in a timely manner, the resulting concentric action should be enhanced beyond the force and power production of a strict concentric-only action.

Also, as mentioned previously, plyometrics involves the projection of the load into space, which means that plyometrics is also a ballistic form of exercise. As a result, the patient is not required to decelerate the load at the terminal end of the concentric phase. This circumstance allows for a longer period of time in which acceleration can occur during the concentric phase. For a thorough review of the benefits of ballistic exercise on velocity, acceleration, force, and power, the reader is recommended to consult Frost et al. [68].

The eccentric prestretch, amortization, and concentric shortening phases are blended in plyometric training to enhance a muscle's performance [7, 24, 30, 33–35, 40, 50, 51, 53, 63, 86]. It is the careful planning through designing periodization programs and execution of the plyometric drills to be described that makes these exercises so effective in performance enhancement.

13.5 Scientific Foundation of Plyometrics

13.5.1 Neuromusculoskeletal Adaptations to Plyometric Training

This section will briefly review the evidence examining the responses and adaptations to plyometric training. For a detailed and comprehensive review specific to the lower extremity, the reader is suggested to consult the paper by Markovic and Mikulic [26]. Prior to briefly reviewing the evidence examining the neuromusculoskeletal adaptations to plyometric exercise, it is important to recognize several factors limiting our current ability to fully understand and synthesize the evidence. First, the participants used in the studies examining the adaptations have varied in age, sex, and activity level. Second, the length of training programs has varied from 4 weeks to 24 months. The specific outcome measures used to reflect the neuromusculoskeletal adaptations have varied extensively. Finally, except for a few studies examining knee and hip kinematics and muscle activation during various landing and jumping tasks, most training studies focused on the ankle. The characteristics of the tendon such as length and stiffness likely influence the extent of muscle fascicle versus tendon elongation during the loading phase of plyometrics, which in turn likely makes the adaptations in responses to training unique for each muscle tendon unit. Thus, with regard to knee rehabilitation, there is a need for additional investigations considering quadriceps and hamstring tendon and muscle fiber, geometry, and contractile element adaptations.

13.5.2 Bone

Typically, following serious acute knee injuries, such as an anterior cruciate ligament (ACL) rupture, there is often a transitory period of lower extremity immobilization and limited weight-bearing. Extending beyond the transitory period of limb protection is often a reduction in physical activity, particularly sport-related participation. Bone, being one of the most metabolically active musculoskeletal tissues, responds to both use and disuse. Thus, it is not surprising that research has demonstrated deficiencies in bone density following knee injury and surgery [87–90]. Based on the high magnitude of loading associated with plyometrics, it would be expected that bone adaptations would occur. Evidence supporting this notion was a conclusion made by Markovic and Mikulic [26] following a review of 18 investigations on bone adaptations to plyometric training. Thirteen of the studies were conducted in children, and the magnitude of bone responses was not universal across all age groups, nor were the lower extremity sites considered. It is important to consider that the studies including adults largely only included pre/postmenopausal women. Additionally, the studies reviewed involved completing plyometrics 3–5 days per week over a 5–24 month period. The large range in the training program length may help explain some of the seemingly contradictory study results. Overall, there was supportive evidence for plyometrics to promote increased bone mass in children and premenopausal women [26]. The effectiveness for plyometrics to prompt bone adaptations in young adult athletes, particularly men, as well as the minimal dosage for plyometrics to prompt bone adaptations remains unknown.

13.5.3 Tendon

Research examining tendon adaptations in response to plyometric training has largely only considered the Achilles tendon [58, 91–97]. The majority of the research on tendon adaptations to plyometric training has assessed cross-sectional area and stiffness. While Kubo et al. [96] and Fouré et al. [91, 92, 98] reported no changes in the cross-sectional area of Achilles tendon, Houghton et al. [94] reported a significant increase. Changes in tendon stiffness in response to plyometrics have been assessed in a variety of manners, yielding some studies [58, 91, 99] to demonstrate increases in stiffness, with others failing to demonstrate stiffness changes [94, 96, 98]. Most recently, Kubo et al. [97] compared 12 weeks of plyometric and isometric training on active and passive muscle stiffness and tendon properties during ramp and ballistic contractions, which are believed to be more reflective of the tendon behavior during running and jumping. The results revealed that the plyometric training increased the extensibility of the tendon during ballistic contractions and active muscle stiffness during fast stretching. These adaptations are attributed with enhancing the storage of elastic energy during SSC activities, which could lead to enhanced athletic performance. Additionally, these adaptations may also have implications for enhancing functional joint stability. Specifically, if the muscle-tendon unit can absorb and store more energy during the eccentric phase of an SSC action, they may stress-shield the ligaments and joint capsule.

13.5.4 Muscle [100]

Restoring and augmenting muscle strength is frequently part of the rationale for using plyometrics following knee injury or surgery. Despite plyometrics being a high-velocity exercise, some research has demonstrated improvements to one repetition maximum [101] and isometric [59, 102, 103] and concentric/eccentric [102] knee extensor strength. Muscle geometry, volume, cross-sectional area, fiber length, and pennation angle are all relevant factors influencing a muscle's ability to produce force. These factors have been considered in various plyometric training studies with conflicting results. For example, increases in triceps surae [96] and thigh muscle volume [4] have been reported; however, four other studies failed to reveal any changes in the gastrocnemius cross-sectional area [91, 92, 104, 105]. Fascicle length and pennation angle also do not appear to be changed by isolated plyometric training [92, 104]. Furthermore, several studies have reported increased maximal voluntary contraction force, but no change in force production during an electrically evoked twitch [59, 76, 96]. Collectively, all of this evidence suggests that neural adaptations are likely responsible for the strength gains associated with plyometric training. In addition, it is commonly thought that plyometrics can enhance the rate of force development. Studies examining knee extension reported a significant rate of force development increase [59, 105], while those considering plantar flexion did not [91, 96]. The differences in results may be attributed to the differences in the muscle-tendon structure and properties.

13.5.5 Neural

Neural adaptations are believed to explain muscle strength gains, particularly those that happen soon after initiating plyometrics. Studies have demonstrated higher levels of voluntary isometric muscle activation following plyometric training [58, 59, 96, 102, 106]. Research examining H reflexes is conflicting, with one report of enhanced (soleus) [107] and one report of no change (vastus medialis) [59]. Even more relevant to knee injury prevention and rehabilitation have been studies demonstrating higher levels of muscle activation during functional activities such as jumping [5, 25, 96, 104], although not all studies have demonstrated changes in muscle activation levels [8, 105].

13.6 Examples of Plyometrics in Athletics

The rapid deceleration–acceleration that occurs when performing plyometrics is an explosive reaction that increases both the speed and power of the limbs during athletic activities [7, 10, 16, 31, 32, 41, 42, 47, 50, 78, 86, 87, 99, 108–111]. This explosive reaction facilitates the production of maximal force in the shortest amount of time. Plyometric training is often considered the missing link between strength and return to performance. There are many examples of plyometric activities in the lower extremities, such as running, jumping, and kicking. The angular velocities of the knee have been recorded at around 1000°/s with each foot contact [112, 113]; there is an eccentric stretch followed by the concentric shortening contraction. Jumping, cutting, and pivoting activities occur in almost all sports, and each has plyometric demands; thus, the concept of power development is the key for many activities of daily living and work-related activities, as well as recreational and competitive sports [7, 33, 42, 43, 46, 78, 108, 111–113]. Realizing the fast angular velocities and tremendous forces required in various activities of daily living and sporting activities illustrates the need for plyometric training in preparing the patient or athlete to return back to their activities. Rehabilitation and conditioning programs are designed to return patients and athletes back to their respective activities as safely and quickly as possible based on functional specific activities. Plyometric exercises should play a critical role in this important role to develop power for performance [7, 40, 41, 43, 47, 50, 78].

13.7 Contraindications for Plyometrics of the Knee

There are relative and absolute contraindications for implementing a plyometric program into a rehabilitation or strength and conditioning program for the knee. These include soft tissue limitations based on postoperative conditions, pain, inflammation, subacute sprains, subacute strains, joint instability, lower extremity weakness, quadriceps weakness, abnormal kinematic movement patterns, selected postsurgical conditions, and knee chondral injuries.

Many of these conditions would also be absolute contraindications for plyometric training of the knee, including soft tissue limitations based on postoperative conditions, pain, inflammation, subacute sprains, subacute strains, joint instability with an unstable knee, lower extremity weakness, quadriceps weakness, abnormal kinematic movement patterns, early postsurgical conditions, and early postoperative knee chondral surgical procedures.

13.8 Theoretical Training Benefits of Plyometric Exercises for the Knee

The theoretical and potential training effects for using plyometric exercise for rehabilitation or performance enhancement of the patient with a knee injury or surgery include, but are not limited to, the following:

1. Research supports the concept that the faster the muscle is loaded eccentrically, the greater is the force produced [114–117];, therefore, the plyometric stretch-shortening cycle should facilitate performance.
2. By desensitizing the muscle spindle, plyometric exercises allow muscles to generate greater forces by having the musculoskeletal system tolerate increased workloads without the Golgi tendon organ firing [53, 57, 63, 117–119].
3. Plyometrics increase neuromuscular coordination by training the nervous system and making movements more automatic during activity (training effect). This is known as reinforcing a motor pattern and creates automation of activity. This improves the neural drive and efficiency and increases the neuromuscular performance [8, 11, 21–26, 62]. The increase of performance often occurs without a concomitant increase in the morphological changes within the muscle. This training effect of the neural system predominates in the first 4–8 weeks of any training program, and after several weeks (>6 to 8), hypertrophic morphological changes of the muscles begin to occur [120].

13.9 Criterion-Based Clinical Guidelines for Beginning a Plyometric Program

Not every patient requires plyometric exercises during the terminal phases of their rehabilitation program. Since most sporting activities involve plyometric motions, and based on the principles of training specificity, exercises, training, and rehabilitation should match the ultimate performance as closely as possible [121–124]. Therefore, only those patients or athletes that need explosive powerful movements for their recreational or competitive athletic activities need to train using plyometric exercises. These types of activities generally occur at faster speeds, incur higher forces, and involve multiple planes of movement. Because general traditional exercises are not matched to the actual demands of sports performance, it has been suggested that plyometric exercises can bridge the gap between rehabilitation and sports-specific activities [16, 33, 40, 41, 78, 110, 111, 125].

When a plyometric training program is initiated, both the athlete and clinician need to be aware of several guidelines. Some of these guidelines are described below, even though the exact parameters for training are not known. However, minimal improvement and increased risk for injury may result if the clinician does not consider some of the aforementioned criterion- based guidelines [34, 35].

Because of the stresses imposed with plyometric training, there are several safety considerations in the program designs that need to be addressed. The age of the patient is an important consideration because of the intensity of plyometrics on the musculoskeletal system, particularly with younger individuals with open physes. There are no absolute guidelines provided in the literature, but precautions for the younger athletes performing a plyometric program after a knee injury or surgery are warranted. The injury history and type of surgery must be taken into consideration to prevent exacerbating an existing or prior deficit [34, 35]. Examples of caution in initiating and progressing a patient in a plyometric program include chondral injuries, osteochondritis dissecans lesions, osteoarthritic changes, ACL injuries (particularly because of the bone contusions that occur), and any chondral surgical procedures (microfractures, mosaicplastys, osteochondral autograft transfer, autologous chondrocyte implantation, DeNova, etc.).

Before initiating a plyometric exercise program, a systematic functional testing algorithm should be performed to screen the patient for the ability to participate. As mentioned previously, it is important to work each link in the kinematic chain to establish an adequate strength base to safely perform these higher level exercises. Table 13.1 provides some empirically-based examples of criteria that have been described in the literature, as well as those used by the authors.

While objective tests have been described, it must be remembered that there is never a good substitute for sound clinical judgment during the assessment of any athletic patient, healthy or injured. This is especially important because guidelines for initiating plyometric exercises during rehabilitation and in healthy population have not been clearly described. None of the proposed criteria have demonstrated predictive validity that if the patient passes the tests, they can successfully navigate through a progressive plyometric program. For instance, Voight et al. [111] indicate that the ability to perform a 30-second single leg stance with eyes open and closed could be used prior to initiating a lower extremity plyometric program. However, most plyometrics (which are dynamic exercises) are performed with eyes open. So, although these criteria are recommended, there is no predictive validity regarding the success of achieving plyometric training. Voight et al. [44, 111, 126] also described the assessment of a single-leg half-squat to be used for a dynamic evaluation prior to initiating the plyometric program.

If the patient can perform the criteria listed in Table 13.1, we have confidence that they can begin the plyometric program without fear of hurting themselves or aggravating the knee and creating a reactive synovitis response. They should have sufficient strength to control their body, with no demonstration of aberrant movement patterns, indicating the neuromuscular system is functioning reasonably well.

Table 13.1 Criterion-based clinical guidelines for application of plyometrics of the knee [16, 35, 111, 133–136]

Tests and methods	Specific criteria for progression
Soft tissue healing	Time-based
Patient-reported outcomes	Within 75–80% of normal limits
Kinesiophobia	Minimal
Pain	None in lower extremities
Swelling[a]	None
Active and passive range of motion	Full in bilateral comparison
Single leg balance: eyes open	30 s
Single leg balance: eyes closed	30 s
Muscle strength: total leg strength with handheld dynamometer	20% bilateral comparison
Muscle power: rate of quadriceps force development with isokinetic testing	20% bilateral comparison, 20% to allometric scaling
Muscle endurance–isokinetic testing	20% bilateral comparison
Neuromuscular control	Qualitatively good movement patterns with no compensations or aberrant movement patterns
Single-leg half-squat	No pain and qualitatively good movement patterns with no compensations
Free weight squat	1.5–2.5 times body weight
Squat: 60% of body weight, five times in 5 s	No pain and qualitatively good movement patterns with no compensations
Double-leg jump	80% of height, ability to control landing, no aberrant movement patterns
Single-leg hop	80% limb symmetry index; 70% of height, ability to control landing, no aberrant movement patterns
Triple hop	80% limb symmetry index; ability to control landing, no aberrant movement patterns
Cross-over hop	80% limb symmetry index; ability to control landing, no aberrant movement patterns
Lower extremity functional test (LEFT)[b]	Time based on normative data; may perform at submaximal intensity to determine patient tolerance
Lower-level plyometric drills	No pain and qualitatively good movement patterns with no compensations

[a]No effusion (will cause an arthrogenic inhibition of the surrounding muscles, particularly the quadriceps muscles)
[b]This test incorporates acceleration, deceleration, front running, retro-running, proactive cutting, and pivoting in both a nonfatigued and a fatigued state at the end of the test

13.10 Designing a Plyometric Program for the Knee

Plyometric training should always be preceded by and coincide with other forms of resistance and flexibility training until an adequate base (foundation) of strength, power, and flexibility has been established. The patient should be able to meet the criterion-based guidelines previously described in Table 13.1 to initiate the plyometric program for both safety and performance reasons. Plyometric exercises then need to be integrated into the totality of the rehabilitation, conditioning, or performance enhancement program. It is critical to evaluate the acute and chronic volume dosage loading on the patient at the beginning and serially throughout the rehabilitation or training programs [35, 127, 128].

When the decision is made that the patient will participate in a plyometric program, an adequate systemic and local tissue warm-up should be performed to help prevent injuries and prepare the neuromusculoskeletal system for the demands of the training. The experience of the athlete and the foundational strength are also critical in the program development, whether in rehabilitation or a performance enhancement training program. The athlete's experience in resistance training programs must be factored into the program to develop and customize the programs to meet their needs. The strength ratio of the athlete is important regarding his/her foundation to begin a plyometric program. Some guidelines have been provided in the literature [30–35, 45–47, 78], such as squatting to two times one's body weight. Most of these guidelines are empirically based from the Russian and Eastern European literature and really do not correlate with clinical applications. These guidelines were probably used for conditioning and performance enhancement programs, and not rehabilitation programs.

The clinician should make the plyometric training program specific to the individual goals of the athlete. We recommend initially that each specific movement pattern involved in the activity needs to be trained in isolation, allowing the sports activity to be dissected into smaller components and trained with isolated movements. Only after each link in the kinematic chain is strengthened to perform its fair share of the workload, should it be integrated back together into a total coordinated movement pattern. If a muscle cannot function normally in an isolated pattern, then it cannot function normally in a functional movement pattern. For best results, the training program should be customized as much as possible to the athlete and his or her sport. As indicated previously, plyometric programs should be integrated into the totality of the present program. One of the better ways to achieve the integrated approach is to use the periodization programming model.

13.10.1 Periodization Program

The concept of periodization is a form of training that has been used in the conditioning of the athletes since the 1950s [125, 129]. Periodized training, in essence, is a training plan that changes the workouts at regular intervals of time. Periodization is the gradual cycling of specificity, volume, intensity, duration, and frequency to achieve peak levels of sport-specific physiological abilities for the most important competitions [125, 129]. Periodization of training is a sequential, systematic, and progressive method of training, which divides the rehabilitation program or training cycle in various periods of specialized training with set goals for the period. The traditional concept of periodization training usually manipulates the variables of volume, intensity, and skill training [125, 129]. This provides the clinician with the opportunity to focus the training to meet the demands of the athlete.

Reasons for using periodized rehabilitation or training include the prevention of a plateau response from occurring by providing manipulation of the different variables and continual stimulation of the patient or athlete. The continual stimulation is accomplished by establishing microcycles during the course of the rehabilitation or training program. The systematic change generates measurable progress that can facilitate the rehabilitation or performance enhancement. The same concept is applied daily by phasing or focusing the rehabilitation program based on the needs of the patient. The concepts of cycles as described in periodization programs are similar to what is actually performed in physical therapy by establishing long-term patient goals (macrocycles), intermediate patient goals (mesocycles), and short-term patient goals (microcycles).

The purpose of discussing periodization is to emphasize that plyometrics should be integrated into a rehabilitation or training program in microcycles in the terminal phases of rehabilitation program, or integrated throughout a strength and conditioning program. The contents of the periodization program regarding the strength, power, endurance, speed, and technical aspects need to be considered and integrated in the development of any plyometric program. Understanding the periodization model as the template of the progressively changing program is an intricate part of plyometric training. The periodization training model takes into consideration the specific demands of the athlete's sport from a technical standpoint and how to best integrate plyometric training to enhance performance. Furthermore, the periodization model considers the time of the year (preseason, in-season, post-season) and the need to peak for certain events. Manipulating the variables previously discussed in the periodization model allows for customizing the needs of the athlete at different times throughout their training cycles [125, 129].

Table 13.2 Plyometric exercise volume (foot contacts) based on athletic ability and exercise intensity [78]

Athletic ability		Exercise intensity	
Level	No. foot contacts	Level	No. foot contacts
Beginner	80–100	Low	400
Intermediate	100–120	Moderate	350
Advanced	120–140	High	300
		Very high	200

13.10.2 Scientific Foundation for the Application of Plyometrics

There is no consensus in the published literature on the specific criteria, parameters, guidelines, specific exercises, or principles of progression that should be used during plyometric training. Most of the recommendations are empirically based upon Level 5 evidence with minimal scientific research supporting any of the recommendations. Table 13.2 provides examples of commonly used guidelines for plyometric training of the lower extremities.

13.10.3 Specific Principles and Concepts: Components of a Plyometric Training Program

There are a variety of plyometric programs described in the literature; however, there are no Level I or Level II studies that definitely indicate the exact volume dosage loading parameters that should be used in a rehabilitation or strength and conditioning program [86, 130, 131]. There are examples of parameters that can be manipulated when designing plyometric activities and progressions for plyometric training programs. All the variables listed need to be considered when designing and exacting a plyometric program. Tables 13.3 and 13.4 provide guidelines that can be used to design plyometric training programs.

13.10.4 Components for Progression of a Plyometric Training Program

Because of the amount of stress created in even lower-level plyometric activities, many exercises are not appropriate for early phases of rehabilitation or individuals who may be deconditioned. Certainly before initiating higher level jump training, lower-level plyometric or plyometric-type activities can be used to test the athlete's tolerance to the plyometric loading response (see Tables 13.3 and 13.4). A progression of plyometric intensity is always prudent, especially in those returning to activity from a previous injury or surgery. There is no consensus in the published literature on the specific criteria, parameters, guidelines, specific exercises, or principles of progression that should be used during plyometric training. Most of the recommendations are empirically based upon Level 5 evidence with minimal scientific research supporting any of the recommendations. Table 13.5 provides examples of the commonly used guidelines for the progression of plyometric training of the lower extremities.

Table 13.3 Parameters that can be manipulated when designing training progressions for plyometric programs

Repetitions
Sets
Frequency
Intensity (submaximal during the beginning phases of training, although maximal intensity plyometrics are most effective)
Pattern of movements
Range of motion (spatial overload)
Temporal overload (timing)
Type of activity
Progression
Volume
Length or duration of training
Rest intervals (recovery)
Resistance weights (body weight, external weighted vests, weights, etc)
Position of patient
Body parts involved in the activity (isolated joint movements vs. multijoint movements)
Effects of fatigue
Specificity
Recovery

13.10.5 Plyometric Techniques

A major consideration when training with plyometric exercise is the need to closely monitor the technique. Acquisition or reacquisition of motor skills should occur to ensure biomechanical

Table 13.4 Examples of principles of progression and overload that may be used for plyometric training

Progress from	To
One plane of motion	Multiple planes of motion
One direction	Multiple directions
One joint isolated exercise	Multiple muscles moving
Nonweight-bearing	Partial weight-bearing, then full weight-bearing
Open kinetic chain	Closed kinetic chain, then functional
Limited range of motion	Full range of motion
Slow velocity of motion	Medium velocity, then fast velocity
Partial movement pattern	Whole movement pattern
Whole movement pattern	Partial, then whole movement pattern
Concentric	Eccentric, then combined
Concentric	Countermovement concentric
Isometric (static)	Dynamic (ballistic)
One movement and stick	Multiple movements and stick
One movement	Repetitive movements
Proactive movements	Reactive movements
General movement patterns	Specificity
Low intensity	Medium, then high
Double-leg drills	Single-leg drills
Forward step-ups	Backward, then lateral
Low step-up height	Medium, then high
Shuffling movement patterns	Carioca
Horizontal bounding	Medial–lateral, then diagonal
Vertical jumping	
Jogging in place	Running in place
Stable surfaces [137]	Minimally unstable (pad), then moderately unstable (Dyna-Disc, tilt boards), then maximally unstable (BOSU)
Full vision	Partially obstructed vision, then stroboscopic interruptions, then eyes closed/blindfolded
Internal focus of attention	External focus
Drills: proactive response	Reactive response
Multiple distractions in performing drills	

Table 13.5 Example of progressions for a plyometric training program

Progress from	To
Warm-up: general systemic	Specific joint
Trunk (core) stability plyometrics: trunk flexion/ extension	Trunk lateral flexion, trunk rotation, trunk PFN functional patterns
General lower extremity plyometrics: isolated of primary joints (ankle plyometrics, single-leg hops)	Total pattern plyometrics (sport-specific plyometric movement patterns)
Jumping activities	Bounding activities
Intensity level: beginner	Intermediate, then advanced
Short-arc range of motion exercises	Full-arc range of motion exercises
Closed kinetic chain exercises (partial range of motion or submaximal)	Open kinetic chain isolated exercises, then closed kinetic chain exercises (full range of motion or maximal intensity)
Perturbation training: beginning submaximal intensity	Slow movement patterns, then known movement patterns (allows subject to preset muscles), to position of stability (2 feet, protected/restricted position)
Perturbation training: advanced maximal intensity	Fast movement patterns, then random patterns (challenges subject to respond to imposed demands) to position of less stability (higher risk position)

safety. Improper technique and compensations should not be allowed, as faulty motor patterns should not be reinforced. Moreover, it could be the athlete's poor motor control that caused the injury [21, 60, 61]. Immediate feedback to poor performance or technique should be provided, as well as continuously increase the awareness of faulty mechanics that might put the athlete at risk of injury or reinjury. Feedback can be provided in various ways, including verbally addressing the aberrant mechanics, video-camera recording, mirror training, or dyad training. Just because the athlete is able to perform the techniques correctly, the clinician should not assume the patients have enough endurance to continue their flawless performance. There is the need for fatigue testing and endurance training. When the athlete's technique declines, the clinician should stop the activity immediately to prevent reinforcing abnormal motor patterns. The goal should be for the athlete to be able to increase the volume of the training sessions via number of repetitions or exercises while still maintaining excellent technique [34, 35, 86, 110, 126]. The use of body weight-supported plyometrics described by Elias et al. [132] may be indicated in the early stages of plyometric training, or if a patient or subject starts to fatigue and demonstrates poor kinematic patterns with compensations.

13.10.6 Examples of Lower Extremity Plyometric Exercises

Competitive sports and recreational activities often require athletic movements that combine both the strength and speed to create the by-product known as power. For years, clinicians have sought ways to increase power in order to enhance performance. In an effort to return athletes to play at the highest levels, clinicians rely on the use of plyometric exercises. In the lower extremity, plyometric exercises are often performed through jumping, bounding, and hopping [30–35, 45–47, 78]. Table 13.6 provides examples of various lower extremity plyometric exercises stratified by the levels of difficulty (Figs. 13.1, 13.2, 13.3, 13.4, 13.5, 13.6, 13.7, 13.8, 13.9, 13.10, 13.11, 13.12, 13.13, 13.14, and 13.15).

Table 13.6 Examples of progression of selected plyometric activities of the knee for rehabilitation and conditioning stratified by intensity [34, 35][a]

Beginner: slow controlled speeds, submaximal intensity, single movement	Single-leg push-off box
	Shuffling
	Ankle bounces
	Skipping
	Jumps in place
	Bilateral submaximal minijumps at slow speeds (single movement) and stick
	Lateral bounding
	Bilateral single movement onto stable landing platform (Fig. 13.1)
Intermediate: medium controlled speeds, moderate intensity, single movement	Bilateral maximal minijumps at medium speeds (single movement) and stick
	Bilateral jumps: anterior, posterior, lateral, diagonal
	Side-to-side push-off jumps
	Zigzag jumps
	Jump and reach
	Bilateral tuck jumps (Fig. 13.2)
	Pike jumps
	Bilateral jump onto plyometric box (Fig. 13.3)
	Step from box
	Lateral bounding (Fig. 13.4)
	Squat jumps
	Bilateral single movement onto a stable landing platform
	Bilateral single movement onto an unstable landing platform (Fig. 13.5)

(continued)

Table 13.6 (continued)

Advanced: fast controlled speeds, maximal intensity, multiple movements	Bilateral maximal minijumps at fast speeds (single movement) and stick
	Bilateral jumps: anterior, posterior, lateral, diagonal
	Single-leg hops
	Single-leg tuck jumps
	Lateral bounding
	Box jumps
	Bilateral jump off plyometric box (depth jump) (Fig. 13.6)
	Drop jump to second box
	Squat depth jump
	Alternating split squat jumps (Fig. 13.7)
	Bilateral single movement onto a stable landing platform
	Tuck jumps
Other Plyometric Exercises	
Bilateral slow to medium-to-fast velocities with single movement onto a stable plyometric box	Bilateral single movement onto an unstable landing platform
	Bilateral single movement onto a stable landing platform with instant perturbations when landing (Fig. 13.8)
	Bilateral single movement onto a stable landing platform with perturbations in air before landing (Fig. 13.9)
	90–180–270–300 circular jumps (good body control) (Fig. 13.10) – One circular motion at a time (90 and back to start, 180 and back to start, etc.) – Perform each of the jumps consecutively returning to starting position after each circular jump – Both directions
Bilateral submax to maximal intensity with multiple movements: controlled bilateral slow to medium to fast velocities with multiple movements	Bilateral multiple squats
	Bilateral multiple anterior jumps
	Bilateral multiple diagonal jumps
	Bilateral multiple lateral jumps
	Bilateral multiple retrojumps
Unilateral submax to maximal intensity with single movement (stick)	(Fig. 13.11)
Unilateral slow to medium to fast with single movement (stick)	Unilateral squats
	Unilateral anterior jumps and stick
	Unilateral anterior jumps and stick on an unstable surface
	Unilateral diagonal jumps
	Unilateral lateral jumps
	Unilateral retrojumps
Unilateral submax to maximal intensity with single movement onto a stable plyometric box	
Unilateral slow to medium to fast with single movement onto an unstable landing platform	(Fig. 13.12)
Unilateral submax to maximal intensity with single movement onto a stable landing platform	With instant perturbations when landing With perturbations in air before landing
Alternating legs, touching the center of target on floor and circling an object	Manipulate arms with weights
Plyometric box jumps: double-leg and single-leg	Jump up first and land on top of box
	Hop up first and land on top of box (Fig. 13.13)
	Depth jumps and landing on both legs
	Depth jumps and landing on single leg (Fig. 13.14)
	Unstable landing surface
	Landing and known reactive pattern (Fig. 13.15)
	Landing and unknown reactive pattern

[a]Changes for progression from beginner to intermediate to advanced will often be based on the following: speed of performance, intensity of performance, single vs multiple movements, short to full range of motion exercises, stable to unstable surfaces, full vision vs obstructed vision, internal vs external focus of attention, proactive vs reactive response during the plyometric movement, and the type of specific plyometric skill

Fig. 13.1 Bilateral single movement onto a stable landing surface exercise can begin with taking off (left) and landing (right) back onto a stable support surface

Fig. 13.2 Bilateral tuck jumps involve flexing the knees and hips maximally while in flight

Fig. 13.3 Bilateral jumping onto a plyometric box can be progressed by increasing the height of the box onto which the athlete lands

Fig. 13.4 Lateral bounding involves laterally jumping from left to right landing on respective lower limbs

Fig. 13.5 Bilateral jumps are performed from the floor (left) onto an unstable surface (right) and can be performed laterally, anteriorly, or posteriorly

Fig. 13.6 Bilateral jumps involve jumping from an elevated surface (left) onto the floor (right). The height from which the jumps are performed can be progressively increased

Fig. 13.7 Alternating split jumps are performed by jumping from a lunge position (left), switching lead limb while airborne (middle), and landing back into a lunge position (right)

Fig. 13.8 Bilateral jumps (left) can be progressed by providing perturbations immediately upon ground contact (right)

Fig. 13.9 Bilateral jumps (left) can also be progressed by providing perturbations while in flight (right)

Fig. 13.10 Circle jumps involve performing a bilateral jump (left) and then rotating in flight to land 90° (middle-left), 180° (middle-right), or 270° (right) from the start position

Fig. 13.11 Single-leg horizontal hops (left) can be progressed by increasing the distance (right) while keeping an emphasis on sticking the landing

Fig. 13.12 Single-leg hopping from the floor (left) to an unstable surface (right) can be progressed through increasing the movement speed

Fig. 13.13 Double and single-leg hops from the floor (left) onto a box (right) can be progressed by increasing the box height and distance

Fig. 13.14 Double and single depth jumps from a box (left) onto the floor (right) can be progressed by increasing the box height and distance

Fig. 13.15 An example of a single-leg landing and unknown reactive pattern drill. In this case, the athlete is jumping from a box (left) and upon ground contact is given a cue (right) about the direction they need to move next

Table 13.7 Functional Testing Algorithm (FTA) for discharge back to activity [16, 35, 133–136]

Discharge/return to practice/return to sports/return to performance
Sports-specific testing
Lower Extremity Functional Test (LEFT) [138, 139]
Functional hop test [138]
Functional jump test [138]
Open kinetic chain isokinetic test [140–143]
Closed kinetic chain isokinetic test [142, 143]
Kinesthetic/proprioception/balance testing
Knee arthrometer test (KT-1000/KT-2000)
Basic measurements
Kinesiophobia test
Patient-reported outcomes
Visual analogue scale/numeric pain rating scale
Protect anterior cruciate ligament graft based on soft tissue healing times
Clinical examination
Physician approval

13.11 Functional Testing Algorithm (FTA) for Clinical Decision-Making for Return to Activity

The senior author has used a lower extremity/knee functional testing algorithm (FTA) for almost 40 years [16, 35, 133–136], as illustrated in Table 13.7. Progression to the next higher level of testing difficulty is predicated upon passing the prior test in the series. Each successive test and its associated training regimen places increasing stress on the patient, while at the same time decreasing clinical control. Not only can the FTA provide a criterion-based approach to return to sport, but it can also serve as a guide for clinical decision-making for treatment interventions. We can rehabilitate patients faster than ever because by testing them, we always know where the patient is in the rehabilitation program, and can focus the interventions specifically on the patient's particular condition and status.

13.12 Summary

This chapter provides an overview of the application of plyometric training and its usage for return to sport after ACL reconstruction and other knee operations while limiting the risk of reinjury and maximizing athletic performance. Unfortunately, there are limited high-level studies that demonstrate plyometrics are effective because they are usually incorporated into a multimodal rehabilitation or training and conditioning program. Nevertheless, plyometrics are and should be included in these programs to accomplish all the goals previously discussed. This chapter provides an introduction, history, definition of phases, scientific foundations, examples of plyometrics in athletics, contraindications for plyometric training, theoretical training benefits, criterion-based guidelines to begin a plyometric program, criteria for designing a program, concept of periodization, specific principles for program design, components for progression, evidence for using plyometrics, plyometric techniques, examples of stratified plyometric exercises, and a functional testing algorithm for criteria for returning a patient/athlete back to activity.

References

1. Adams K, O'Shea JP, O'Shea KL, Climstein M. The effect of six weeks of squat, plyometric and squat-plyometric training on power production. J Strength Cond Res. 1992;6(1):36–41.
2. Bedi JF, Cresswell AG, Engel TJ, Nicol SM. Increase in jumping height associated with maximal effort vertical depth jumps. Res Q Exerc Sport. 1987;58(1):11–5.
3. Brown AC, Wells TJ, Schade ML, Smith DL, Fehling PC. Effects of plyometric training versus traditional weight training on strength, power, and aesthetic jumping ability in female collegiate dancers. J Dance Med Sci. 2007;11(2):38–44.
4. Chelly MS, Hermassi S, Aouadi R, Shephard RJ. Effects of 8-week in-season plyometric training on upper and lower limb performance of elite adolescent handball players. J Strength Cond Res. 2014;28(5):1401–10. https://doi.org/10.1519/jsc.0000000000000279.
5. Chimera NJ, Swanik KA, Swanik CB, Straub SJ. Effects of plyometric training on muscle-activation strategies and performance in female athletes. J Athl Train. 2004;39(1):24–31.
6. de Villarreal ES, Kellis E, Kraemer WJ, Izquierdo M. Determining variables of plyometric training for improving vertical jump height performance: a meta-analysis. J Strength Cond Res. 2009;23(2):495–506. https://doi.org/10.1519/JSC.0b013e318196b7c6.

7. Duda M. Plyometrics: a legitimate form of power training? Phys Sportsmed. 1988;16(3):212–8.
8. Kyröläinen H, Avela J, McBride JM, Koskinen S, Andersen J, Sipilä S, Takala T, Komi P. Effects of power training on muscle structure and neuromuscular performance. Scand J Med Sci Sports. 2005;15(1):58–64.
9. Ramachandran S, Pradhan B. Effects of short-term two weeks low intensity plyometrics combined with dynamic stretching training in improving vertical jump height and agility on trained basketball players. Indian J Physiol Pharmacol. 2014;58(2):133–6.
10. Ramírez-Campillo R, Andrade DC, Izquierdo M. Effects of plyometric training volume and training surface on explosive strength. J Strength Cond Res. 2013;27(10):2714–22.
11. Wilkerson GB, Colston MA, Short NI, Neal KL, Hoewischer PE, Pixley JJ. Neuromuscular changes in female collegiate athletes resulting from a plyometric jump-training program. J Athl Train. 2004;39(1):17–23.
12. Chaouachi A, Hammami R, Kaabi S, Chamari K, Drinkwater EJ, Behm DG. Olympic weightlifting and plyometric training with children provides similar or greater performance improvements than traditional resistance training. J Strength Cond Res. 2014;28(6):1483–96. https://doi.org/10.1519/jsc.0000000000000305.
13. Franco-Márquez F, Rodríguez-Rosell D, Gonzalez-Suarez J, Pareja-Blanco F, Mora-Custodio R, Yanez-Garcia J, González-Badillo J. Effects of combined resistance training and plyometrics on physical performance in young soccer players. Int J Sports Med. 2015;94(11):906–14.
14. Vaczi M, Tollar J, Meszler B, Juhasz I, Karsai I. Short-term high intensity plyometric training program improves strength, power and agility in male soccer players. J Hum Kinet. 2013;36:17–26. https://doi.org/10.2478/hukin-2013-0002.
15. Vissing K, Brink M, Lønbro S, Sørensen H, Overgaard K, Danborg K, Mortensen J, Elstrøm O, Rosenhøj N, Ringgaard S. Muscle adaptations to plyometric vs. resistance training in untrained young men. J Strength Cond Res. 2008;22(6):1799–810.
16. Davies GJ, Riemann B, Ellenbecker T. Role of isokinetic testing and training after ACL injury and reconstruction. In: Noyes FR, Barber-Westin S, editors. ACL injuries in the female athlete: causes, impacts, and conditioning programs. Berlin: Springer; 2018. p. 567–88. https://doi.org/10.1007/978-3-662-56558-2_24.
17. Fatouros IG, Jamurtas AZ, Leontsini D, Taxildaris K, Aggelousis N, Kostopoulos N, Buckenmeyer P. Evaluation of plyometric exercise training, weight training, and their combination on vertical jumping performance and leg strength. J Strength Cond Res. 2000;14(4):470–6.
18. Rimmer E, Sleivert G. Effects of a plyometrics intervention program on sprint performance. J Strength Cond Res. 2000;14(3):295–301.
19. Rodríguez-Rosell D, Franco-Márquez F, Pareja-Blanco F, Mora-Custodio R, Yáñez-García JM, González-Suárez JM, González-Badillo JJ. Effects of 6 weeks resistance training combined with plyometric and speed exercises on physical performance of pre-peak-height-velocity soccer players. Int J Sports Physiol Perform. 2016;11(2):240–6.
20. Saez de Villarreal E, Requena B, Cronin JB. The effects of plyometric training on sprint performance: a meta-analysis. J Strength Cond Res. 2012;26(2):575–84. https://doi.org/10.1519/JSC.0b013e318220fd03.
21. Buchwald JS. Exteroceptive reflexes and movement. Am J Phys Med Rehabil. 1967;46:121–8.
22. Ebben WP, VanderZanden T, Wurm BJ, Petushek EJ. Evaluating plyometric exercises using time to stabilization. J Strength Cond Res. 2010;24(2):300–6.
23. Hutton RS, Atwater SW. Acute and chronic adaptations of muscle proprioceptors in response to increased use. Sports Med. 1992;14(6):406–21.
24. Komi P. Neuromuscular performance: factors influencing force and speed production. Scand J Sports Sci. 1979;1:2–15.
25. Kyrölänen H, Komi P, Kim D. Effects of power training on neuromuscular performance and mechanical efficiency. Scand J Med Sci Sports. 1991;1(2):78–87.
26. Markovic G, Mikulic P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. Sports Med. 2010;40(10):859–95.
27. Makaruk H, Czaplicki A, Sacewicz T, Sadowski J. The effects of single versus repeated plyometrics on landing biomechanics and jumping performance in men. Biol Sport. 2014;31(1):9.
28. Struminger AH, Lewek MD, Goto S, Hibberd E, Blackburn JT. Comparison of gluteal and hamstring activation during five commonly used plyometric exercises. Clin Biomech (Bristol, Avon). 2013;28(7):783–9.
29. Allerheiligen B, Rogers R. Plyometrics program design. Strength Cond J. 1995;17(4):26–31.
30. Chu DA, Plummer L. The language of plyometrics. Strength Cond J. 1984;6(5):30–1.
31. Chu DA, Panariello RA. Jumping into plyometrics: sport specific plyometrics: baseball pitching. Nat Strength Cond Assn J. 1989;11:81–5.
32. Chu DA. Jumping into plyometrics. Champaign, IL: Leisure Press; 1992.
33. Chu DA, Cordier DJ. Plyometrics in rehabilitation. In: Ellenbecker TS, editor. Knee ligament rehabilitation. New York: Churchill Livingstone; 2000.
34. Davies GJ, Matheson JW. Shoulder plyometrics. Sports Med Arthrosc Rev. 2001;9(1):1–18.
35. Davies G, Riemann BL, Manske R. Current concepts of plyometric exercise. Int J Sports Phys Ther. 2015;10(6):760–86.
36. Gambetta V, Odgers S. The complete guide to medicine ball training. Sarasota, FL: Optimum Sports Training; 1991.
37. Heiderscheit B, Rucinski T. Biomechanical and physiologic basis of closed kinetic chain exercises in

the upper extremities. Orthop Phys Ther Clin North Am. 2000;9(2):209–18.
38. Hill J, Leiszler M. Review and role of plyometrics and core rehabilitation in competitive sport. Curr Sports Med Rep. 2011;10(6):345–51.
39. Miyaguchi K, Demura S. Gender difference in ability using the stretch-shortening cycle in the upper extremities. J Strength Cond Res. 2009;23(1):231–6.
40. Lundin P. Plyometrics: a review of plyometric training. Strength Cond J. 1985;7(3):69–76.
41. Lundin P, Berg W. Plyometrics: a review of plyometric training. Strength Cond J. 1991;13(6):22–34.
42. Radcliffe JC, Farentinos RC. Plyometrics: explosive power training. Champaign, IL: Human Kinetics; 1985.
43. Tyler TF, Cuoco A. Plyometric training and drills. In: Andrews JR, Harrelson GL, Wilk KE, editors. Physical rehabilitation of the injured athlete. 3rd ed. Philadelphia: Saunders; 2004.
44. Voight M. Stretch-strengthening: an introduction to plyometrics. Orthop Phys Ther Clin North Am. 1992;1:243–52.
45. Chu DC. Plyometrics: the link between strength and speed. Strength Cond J. 1983;5(2):20–1.
46. Chu DA. Plyometric exercises with the medicine ball. Livermore, CA: Bittersweet Publishing; 1989.
47. Chu DA. Explosive power and strength. Champaign, IL: Human Kinetics; 1996.
48. Verkhoshansky Y. Perspectives in the improvement of speed-strength preparation of jumpers. Yessis Rev Sov Phys Educ Sports. 1969;4:28–34.
49. Verkhoshansky Y. Depth jumping in the training of jumpers. Track Tech. 1973;51:1618–9.
50. Wathen D. Literature review: explosive/plyometric exercises. Strength Cond J. 1993;15(3):17–9.
51. Wilt F. Plyometrics: what it is and how it works. Athl J. 1975;55(5):89–90.
52. Davies GJ. The need for critical thinking in rehabilitation. J Sport Rehabil. 1995;4(1):1–22.
53. Bosco C, Komi PV. Potentiation of the mechanical behavior of the human skeletal muscle through prestretching. Acta Physiol Scand. 1979;106(4):467–72.
54. Bosco C, Komi PV, Ito A. Prestretch potentiation of human skeletal muscle during ballistic movement. Acta Physiol Scand. 1981;111(2):135–40.
55. Fiebert I, Hardy CJ, Werner KL. Electromyographic analysis of the quadriceps femoris during isokinetic eccentric activation. Isokinet Exerc Sci. 1992;2(1):18–23.
56. Knuttgen HG, Klausen K. Oxygen debt in short-term exercise with concentric and eccentric muscle contractions. J Appl Physiol. 1971;30(5):632–5.
57. Wilson JM, Flanagan EP. The role of elastic energy in activities with high force and power requirements: a brief review. J Strength Cond Res. 2008;22(5):1705–15.
58. Wu YK, Lien YH, Lin KH, Shih TT, Wang TG, Wang HK. Relationships between three potentiation effects of plyometric training and performance. Scand J Med Sci Sports. 2010;20(1):e80–6. https://doi.org/10.1111/j.1600-0838.2009.00908.x.
59. Behrens M, Mau-Moeller A, Bruhn S. Effect of plyometric training on neural and mechanical properties of the knee extensor muscles. Int J Sports Med. 2014;35(02):101–19.
60. Riemann BL, Lephart SM. The sensorimotor system, part I: the physiologic basis of functional joint stability. J Athl Train. 2002;37(1):71.
61. Riemann BL, Lephart SM. The sensorimotor system, part II: the role of proprioception in motor control and functional joint stability. J Athl Train. 2002;37(1):80.
62. Rowinski M. Afferent neurobiology of the joint. In: Gould JA, Davies GJ, editors. Orthopaedic and sports physical therapy. St. Louis: C.V. Mosby; 1985. p. 50–65.
63. Asmussen E, Bonde-Petersen F. Storage of elastic energy in skeletal muscles in man. Acta Physiol Scand. 1974;91(3):385–92.
64. Bosco C, Viitasalo J, Komi P, Luhtanen P. Combined effect of elastic energy and myoelectrical potentiation during stretch-shortening cycle exercise. Acta Physiol Scand. 1982;114(4):557–65.
65. Cavagna G, Saibene F, Margaria R. Effect of negative work on the amount of positive work performed by an isolated muscle. J Appl Physiol. 1965;20(1):157–8.
66. Cavagna GA, Dusman B, Margaria R. Positive work done by a previously stretched muscle. J Appl Physiol. 1968;24(1):21–32. https://doi.org/10.1152/jappl.1968.24.1.21.
67. Thys H, Faraggiana T, Margaria R. Utilization of muscle elasticity in exercise. J Appl Physiol. 1972;32(4):491–4.
68. Frost DM, Cronin J, Newton RU. A biomechanical evaluation of resistance. Sports Med. 2010;40(4):303–26.
69. van Ingen Schenau GJ, de Koning JJ, de Groot G. Optimisation of sprinting performance in running, cycling and speed skating. Sports Med. 1994;17(4):259–75.
70. Cavagna G, Mazzanti M, Heglund N, Citterio G. Storage and release of mechanical energy by active muscle: a non-elastic mechanism? J Exp Biol. 1985;115(1):79–87.
71. Newton RU, Murphy AJ, Humphries BJ, Wilson GJ, Kraemer WJ, Häkkinen K. Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. Eur J Appl Physiol Occup Physiol. 1997;75(4):333–42.
72. Nicol C, Avela J, Komi PV. The stretch-shortening cycle : a model to study naturally occurring neuromuscular fatigue. Sports Med. 2006;36(11):977–99.
73. McBride JM, McCaulley GO, Cormie P. Influence of preactivity and eccentric muscle activity on concentric performance during vertical jumping. J Strength Cond Res. 2008;22(3):750–7.

74. Cavanagh PR, Komi PV. Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. Eur J Appl Physiol Occup Physiol. 1979;42(3):159–63.
75. Cavagna GA. Elastic bounce of the body. J Appl Physiol. 1970;29(3):279–82. https://doi.org/10.1152/jappl.1970.29.3.279.
76. Grosset J-F, Piscione J, Lambertz D, Pérot C. Paired changes in electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training. Eur J Appl Physiol. 2009;105(1):131.
77. Wilson GJ, Elliott BC, Wood G. The effect on performance of imposing a delay during a stretch-shorten. Med Sci Sports Exerc. 1991;23(3):364–70.
78. Chmielewski TL, Myer GD, Kauffman D, Tillman SM. Plyometric exercise in the rehabilitation of athletes: physiological responses and clinical application. J Orthop Sports Phys Ther. 2006;36(5):308–19. https://doi.org/10.2519/jospt.2006.2013.
79. Fukunaga T, Kawakarni Y, Muraoka T, Kanehisa H. Muscle and tendon relations in humans: power enhancement in counter-movement exercise. Adv Exp Med Biol. 2002;508:501–5.
80. Kawakami Y, Muraoka T, Ito S, Kanehisa H, Fukunaga T. In vivo muscle fibre behaviour during counter-movement exercise in humans reveals a significant role for tendon elasticity. J Physiol. 2002;540(2):635–46.
81. Clarkson PM, Byrnes WC, Gillisson E, Harper E. Adaptation to exercise-induced muscle damage. Clin Sci. 1987;73(4):383–6.
82. Davies GJ, Ellenbecker TS. Eccentric isokinetics. Orthop Phys Ther Clin North Am. 1992;1(2):297–336.
83. Fridén J, Seger J, Sjöström M, Ekblom B. Adaptive response in human skeletal muscle subjected to prolonged eccentric training. Int J Sports Med. 1983;4(03):177–83.
84. Komi PV, Buskirk E. Effect of eccentric and concentric muscle conditioning on tension and electrical activity of human muscle. Ergonomics. 1972;15(4):417–34.
85. Komi PV, Rusko H. Quantitative evaluation of mechanical and electrical changes during fatigue loading of eccentric and concentric work. Scand J Rehabil Med Suppl. 1974;3:121–6.
86. Holcomb WR, Kleiner DM, Chu DA. Plyometrics: considerations for safe and effective training. Strength Cond J. 1998;20(3):36–41.
87. Murtagh CF, Nulty C, Vanrenterghem J, O'Boyle A, Morgans R, Drust B, Erskine RM. The neuromuscular determinants of unilateral jump performance in soccer players are direction-specific. Int J Sports Physiol Perform. 2018;13(5):604–11.
88. Nyland J, Fisher B, Brand E, Krupp R, Caborn DN. Osseous deficits after anterior cruciate ligament injury and reconstruction: a systematic literature review with suggestions to improve osseous homeostasis. Arthroscopy. 2010;26(9):1248–57.
89. Reiman MP, Rogers ME, Manske RC. Interlimb differences in lower extremity bone mineral density following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2006;36(11):837–44.
90. van Meer B, Waarsing J, van Eijsden W, Meuffels D, van Arkel E, Verhaar J, Bierma-Zeinstra S, Reijman M. Bone mineral density changes in the knee following anterior cruciate ligament rupture. Osteoarthr Cartil. 2014;22(1):154–61.
91. Fouré A, Nordez A, Cornu C. Plyometric training effects on Achilles tendon stiffness and dissipative properties. J Appl Physiol. 2010;109(3):849–54.
92. Fouré A, Nordez A, McNair P, Cornu C. Effects of plyometric training on both active and passive parts of the plantarflexors series elastic component stiffness of muscle–tendon complex. J Appl Physiol. 2011;111(3):539–48.
93. Hirayama K, Iwanuma S, Ikeda N, Yoshikawa A, Ema R, Kawakami Y. Plyometric training favors optimizing muscle–tendon behavior during depth jumping. Front Physiol. 2017;8:16.
94. Houghton LA, Dawson BT, Rubenson J. Effects of plyometric training on achilles tendon properties and shuttle running during a simulated cricket batting innings. J Strength Cond Res. 2013;27(4):1036–46.
95. Ishikawa M, Komi PV. Effects of different dropping intensities on fascicle and tendinous tissue behavior during stretch-shortening cycle exercise. J Appl Physiol. 2004;96(3):848–52.
96. Kubo K, Morimoto M, Komuro T, Yata H, Tsunoda N, Kanehisa H, Fukunaga T. Effects of plyometric and weight training on muscle-tendon complex and jump performance. Med Sci Sports Exerc. 2007;39(10):1801–10.
97. Kubo K, Ishigaki T, Ikebukuro T. Effects of plyometric and isometric training on muscle and tendon stiffness in vivo. Physiol Rep. 2017;5(15):e13374.
98. Fouré A, Nordez A, Guette M, Cornu C. Effects of plyometric training on passive stiffness of gastrocnemii and the musculo-articular complex of the ankle joint. Scand J Med Sci Sports. 2009;19(6):811–8.
99. Burgess KE, Connick MJ, Graham-Smith P, Pearson SJ. Plyometric vs. isometric training influences on tendon properties and muscle output. J Strength Cond Res. 2007;21(3):986.
100. Elftman H. Biomechanics of muscle with particular application to studies of gait. J Bone Joint Surg Am. 1966;48(2):363–77.
101. Saez-Saez de Villarreal E, Requena B, Newton RU. Does plyometric training improve strength performance? A meta-analysis. J Sci Med Sport. 2010;13(5):513–22. https://doi.org/10.1016/j.jsams.2009.08.005.
102. Behrens M, Mau-Moeller A, Mueller K, Heise S, Gube M, Beuster N, Herlyn PK, Fischer D-C, Bruhn S. Plyometric training improves voluntary activation and strength during isometric, concentric and eccentric contractions. J Sci Med Sport. 2016;19(2):170–6.

103. Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. Eur J Appl Physiol. 2003;89(1):1–7.
104. Kannas TM, Kellis E, Amiridis IG. Incline plyometrics-induced improvement of jumping performance. Eur J Appl Physiol. 2012;112(6): 2353–61.
105. Kyröläinen H, Avela J, McBride J, Koskinen S, Andersen J, Sipilä S, Takala T, Komi P. Effects of power training on mechanical efficiency in jumping. Eur J Appl Physiol. 2004;91(2-3):155–9.
106. Bigland B, Lippold OC. The relation between force, velocity and integrated electrical activity in human muscles. J Physiol. 1954;123(1):214–24.
107. Voigt M, Chelli F, Frigo C. Changes in the excitability of soleus muscle short latency stretch reflexes during human hopping after 4 weeks of hopping training. Eur J Appl Physiol Occup Physiol. 1998;78(6):522–32.
108. Costello F. Bounding to the top: the complete book on plyometric training. West Bowie, MD: Athletic Training Consultants; 1990.
109. Ebben WE, Blackard DQ, Jensen RL. Quantification of medicine ball vertical impact forces: estimating effective training loads. J Strength Cond Res. 1999;13(3):271–4.
110. Ernst G, Moore J, VanLunen B, Ball D. Pondering plyometrics. J Orthop Sports Phys Ther. 1997;25(5):350–2.
111. Voight ML, Tippett SR. Plyometric exercise. In: Prentice W, Voight M, Hoogenboom B, editors. Musculoskeletal interventions: techniques for therapeutic exercise. New York: McGraw-Hill Publishing; 2006.
112. Davies GJ. A compendium of isokinetics in clinical usage. 1st ed. La Crosse, WI: S & S Publishers; 1984.
113. Davies GJ. A compendium of isokinetics in clinical usage. Onalaska, WI: S & S Publishers; 1992.
114. Albert M. Eccentric muscle training in sports and orthopaedics. New York: Churchill Livingstone; 1991.
115. DeNuccio DK, Davies GJ, Rowinski MJ. Comparison of quadriceps isokinetic eccentric and isokinetic concentric data using a standard fatigue protocol. Isokinet Exerc Sci. 1991;1(2):81–6.
116. Ebben WP, Simenz C, Jensen RL. Evaluation of plyometric intensity using electromyography. J Strength Cond Res. 2008;22(3):861–8.
117. Ebben WP, Fauth ML, Kaufmann CE, Petushek EJ. Magnitude and rate of mechanical loading of a variety of exercise modes. J Strength Cond Res. 2010;24(1):213–7.
118. Eldred E. Functional implications of dynamic and static components of the spindle response to stretch. Am J Phys Med Rehabil. 1967;46(1):129–40.
119. Wilson GJ, Murphy AJ, Giorgi A. Weight and plyometric training: effects on eccentric and concentric force production. Can J Appl Physiol. 1996;21(4):301–15.
120. Moritani T. Neural factors versus hypertrophy in the time course of muscle strength gain. Am J Phys Med. 1979;58(3):115–30.
121. Davies GJ. Open kinetic chain assessment and rehabilitation. Athl Train Sports Health Care Perspect. 1995;1(4):347–70.
122. Davies GJ, Heiderscheit BC, Konin J. Open and closed kinetic chain exercises: functional application in orthopedics. In: Wadsworth C, editor. Strength and conditioning applications in orthopedics (home study course 98A). Alexandria, VA: Orthopedic Section APTA; 1998. p. 1–19.
123. Davies GJ, Heiderscheit BC, Clark M. Open and closed kinetic chain rehabilitation. In: Ellenbecker TS, editor. Knee ligament rehabilitation. New York: Churchill Livingstone; 2000. p. 291–300.
124. Davies GJ. The scientific and clinical rationale for the integrated approach to open and closed kinetic chain rehabilitation. Ortho Phys Ther Clin North Am. 2000;9:247–67.
125. Davies GJ. Application of the concepts of periodization to rehabilitation. In: Bandy WD, editor. Current trends in therapeutic exercise for the rehabilitation of the athlete (home study course). La Crosse, WI: SPTS; 1997.
126. Voight ML, Hardin JA, Blackburn TA, Tippett S, Canner GC. The effects of muscle fatigue on and the relationship of arm dominance to shoulder proprioception. J Orthop Sports Phys Ther. 1996;23(6):348–52.
127. Jarvis MM, Graham-Smith P, Comfort P. A methodological approach to quantifying plyometric intensity. J Strength Cond Res. 2016;30(9):2522–32.
128. Jensen RL, Ebben WP. Quantifying plyometric intensity via rate of force development, knee joint, and ground reaction forces. J Strength Cond Res. 2007;21(3):763–7.
129. Fleck SJ, Kraemer WJ. Periodization breakthrough: the ultimate training system. New York: Advanced Research Press; 1996.
130. American College of Sports Medicine. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. Med Sci Sports Exerc. 2009;41(3):687–708. https://doi.org/10.1249/MSS.0b013e3181915670.
131. Baechle TR, Earle RW. Essentials of strength training and conditioning: national strength and conditioning association. 3rd ed. Champaign, IL: Human Kinetics; 2008.
132. Elias AR, Hammill CD, Mizner RL. The effect of body weight support on kinetics and kinematics of a repetitive plyometric task. J Appl Biomech. 2016;32(1):69–77. https://doi.org/10.1123/jab.2015-0077.
133. Davies GJ, Zillmer DA. Functional progression of a patient through a rehabilitation program. Orthop Phys Ther Clin North Am. 2000;9:103–18.
134. Davies GJ. Individualizing the return to sports after anterior cruciate ligament reconstruction. Oper Tech Orthop. 2017;27(1):70–8.

135. Davies GJ, McCarty E, Provencher M, Manske RC. ACL return to sport guidelines and criteria. Curr Rev Musculoskelet Med. 2017;10:307–14. https://doi.org/10.1007/s12178-017-9420-9.
136. Manske RC, DeCarlo M, Davies GJ, Paterno MV. Anterior cruciate ligament reconstruction: rehabilitation concepts. Orthop Knowledge Online J. 2017;15(3):1–8.
137. Crowther RG, Spinks WL, Leicht AS, Spinks CD. Kinematic responses to plyometric exercises conducted on compliant and noncompliant surfaces. J Strength Cond Res. 2007;21(2):460–5. https://doi.org/10.1519/r-19645.1.
138. Ellenbecker TS, Davies GJ. Closed kinetic chain exercises: a comprehensive guide to multiple joint exercise. Champaign, IL: Human Kinetics; 2001.
139. Tabor MA, Davies GJ, Kernozek TW, Negrete RJ, Hudson V. A multicenter study of the test–retest reliability of the lower extremity functional test. J Sport Rehabil. 2002;11(3):190–201.
140. Binder D, Brown-Cross D, Shamus E, Davies G. Peak torque, total work and power values when comparing individuals with Q-angle differences. Isokinet Exerc Sci. 2001;9(1):27–30.
141. Davies GJ, Wilk KE, Ellenbecker TS. Assessment of strength. In: Malone TR, McPoil TO, Nitz AJ, editors. Orthopedic and sports physical therapy. St. Louis: Mosby; 1997. p. 225–56.
142. Davies GJ, Ellenbecker TS. The scientific and clinical application of isokinetics in evaluation and treatment of the athlete. In: Andrews JR, Harrelson GL, Wilk KE, editors. Physical rehabilitation of the injured athlete. 2nd ed. Philadelphia, PA: W.B. Saunders; 1999. p. 219–59.
143. Davies GJ, Heiderscheit BC, Brinks K. Test interpretation. In: Brown LE, editor. Isokinetics in human performance. Champaign, IL: Human Kinetics; 2000. p. 1–24.

14 Running, Agility, and Sportsmetrics Training

Sue Barber-Westin and Frank R. Noyes

14.1 Introduction

The majority of patients who sustain anterior cruciate ligament (ACL) injuries and undergo reconstruction are young athletes. The major goals of this operation for these individuals are to stabilize the knee to prevent future reinjuries and allow a safe return to sports (RTS). Although these goals are successfully achieved in many patients, several clinical studies have reported reinjury rates to either the ACL-reconstructed knee or contralateral ACL ranging from 3 to 22% [1–18]. Frequently cited factors associated with reinjuries to either knee are younger patient age, return to high-impact sports that involve cutting and pivoting, and use of an allograft or hamstring autograft. It is important to note that ACL reconstructions may also fail for other reasons such as surgical errors (use of low-strength grafts, inadequate fixation, graft impingement in the notch, or excessive or insufficient graft tensioning at surgery); failure of graft integration, tendon-to-bone healing, or remodeling; uncorrected lateral, posterolateral, or medial ligament deficiency; postoperative infection, and inadequate rehabilitation.

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

A lack of consensus exists regarding the appropriate criteria for releasing patients to unrestricted sports activities after ACL reconstruction. We conducted a systematic review that examined the factors investigators have used to determine when RTS is appropriate [19]. Of the 264 studies included, only 35 (13%) provided objective criteria such as muscle strength or thigh circumference measurements (28 studies), general knee examination parameters such as knee motion and joint effusion (15 studies), single-leg hop tests (10 studies), Lachman rating (1 study), and responses to validated questionnaires (1 study).

We believe that a comprehensive rehabilitation program following ACL reconstruction is crucial to enable patients to RTS as safely as possible. Because of the published documentation of neuromuscular deficits in both the reconstructed and contralateral limbs postoperatively [20], failure to address and fully rehabilitate both knees may also be a factor for high postoperative reinjury rates. RTS is not encouraged early after ACL reconstruction and especially in patients who undergo concomitant major operative procedures such as a complex meniscal repair, other ligament reconstruction, patellofemoral realignment, articular cartilage restorative procedure, or osteotomy. Strenuous athletics are not recommended in patients undergoing revision ACL reconstruction or those in whom magnetic resonance imaging or arthroscopic evidence of major bone bruising or articular cartilage damage exists.

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_14

These patients are entered into a postoperative protocol that incorporates delays in return of full weight-bearing, initiation of certain strengthening and conditioning exercises, beginning running and agility drills, and return to full sports activities [21].

The necessity for preoperative rehabilitation is addressed in Chap. 8 and our early postoperative rehabilitation is detailed in Chap. 11. This chapter provides our recommendations for basic and advanced neuromuscular training, as well as extensive objective criteria required for RTS, based on over three decades of experience and multiple clinical studies [19, 21–25]. The Sportsmetrics program is detailed for end-stage rehabilitation for athletes desiring to RTS that require cutting, pivoting, and repetitive jumping. Multiple studies have been conducted that scientifically justify this program's ability to reduce the incidence of noncontact ACL injuries, improve deficiencies in neuromuscular indices, and enhance athletic performance indicators [26–31].

14.2 Running and Agility Program

Patients are allowed to begin the running program when they demonstrate no more than a 30% deficit on isokinetic testing (isometric mode) for peak quadriceps and hamstrings torque; have a normal Lachman examination (≤3 mm increased anteroposterior tibial displacement); and have no pain, swelling, or instability with all other rehabilitation activities. Although some patients may reach these goals as early as 12 weeks after surgery, the majority are 16–20 weeks postoperative. Only in exceptional cases does this program begin before this time period where muscle strength has returned to normal, no pain or joint effusion is present, and no concurrent major operative procedures were performed. There are four levels in the running program (Table 14.1). Patients are progressed to level 2 when they demonstrate no more than a 20% deficit on isokinetic testing (180°/s and 300°/s) for peak quadriceps and hamstrings torque, provided they are not experiencing pain or swelling with their current activities. They should also demonstrate no more than a 15% difference in limb symmetry on a single-leg hop test. Progression to levels 3 and 4 are done gradually as the patient regains confidence in performing agility drills, cutting, and sharp directional angular movement patterns.

Table 14.1 Levels of the running and agility program

Level	Details
1	Perform on a track to control the surface, ensure a level terrain, and to be able to measure distance. Use straight-ahead run–walk combinations. Running distances 20, 40, 60, 100 yards (18.29, 36.58, 54.86, 91.44 m) in forward and backward directions Speed: ¼ to ½ of normal. Gradually progress to ¾ and then to full speed Interval training–rest approach: rest —two to three times the length of training
2	Lateral running, crossover maneuvers over 20 yards (18.29 m) Side-to-side running over cups Sports-specific equipment used to enhance skill development
3	Figure-eight drills over 20 yards (18.29 m) and then decrease to 10 yards (9.14 m)
4	Cutting patterns, directional changes at 45° and 90° angles, progress from subtle to sharp cuts

The running and agility program may be slightly modified based on the patient's athletic goals, particularly the position or physical requirements of the activity. For instance, an individual returning back to short-duration, high-intensity activities should participate in a sprinting program rather than a long-distance endurance program. This program is performed three times per week, on opposite days of the strength program (see also Chap. 11). Since desired aerobic levels may not be achieved initially, a cross-training program is used to facilitate cardiovascular fitness. The cross-training program is performed on the same day as the strength workout.

14.3 Basic Plyometric Training Program

Basic plyometric training is begun upon successful completion of the running and agility program in order to correct bilateral alterations in neuromuscular function. Jump training should be done on a firm, yet forgiving surface such as a wooden gym floor. Very hard surfaces like concrete should be avoided. A cross-training or running shoe should be worn to provide adequate shock absorption and stability to the foot.

During the jumps, the patient is instructed to keep the body weight on the balls of the feet and to jump and to land softly with the knees flexed. The knees should be kept shoulder-width apart to avoid knee hyperextension and an overall valgus lower limb position. The patient should understand that the exercises are reaction and agility drills and while speed is emphasized, correct body posture must be maintained throughout the jumps (Fig. 14.1).

Plyometric training is performed —two to three times weekly. There are six levels in the basic plyometric training program (Table 14.2). The rest period initially lasts two to three times the length of the exercise period, which is gradually decreased to one to two times. The starting exercise time period is 15 s per direction. The patient is asked to complete as many hops between the squares as possible. Three sets are performed for both directions and the number of hops is recorded. The program is progressed as the number of hops increases, along with patient confidence.

14.4 Sportsmetrics Neuromuscular Retraining

Advanced neuromuscular retraining such as the Sportsmetrics program is advocated as end-stage rehabilitation for all patients returning to

Table 14.2 Levels of the basic plyometric training program

Level	Jumps
1	Level surface box hopping, both legs, four-square grid on floor: front–back and side-side
2	Level surface box hopping, both legs: hop in L-shaped and reverse L-shaped directions
3	Level surface box hopping, both legs: diagonal
4	Level surface box hopping, both legs: pivot hops, 90° and 180° directions
5	Level surface box hopping, single leg: front–back, side-side, diagonal, pivot hops 90° and 180°
6	Vertical box hops

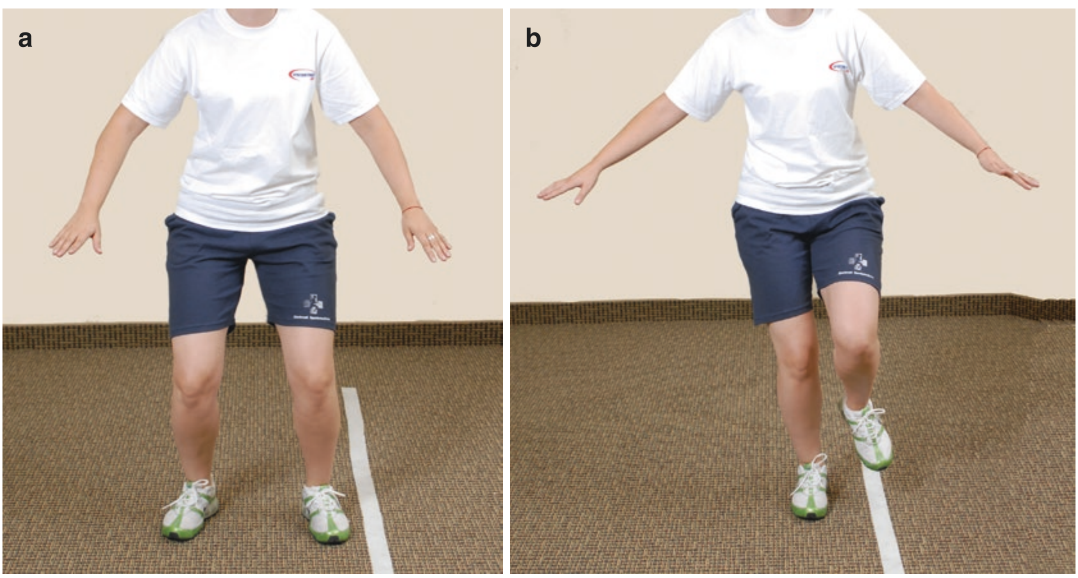


Fig. 14.1 Plyometric training with the demonstration of correct body posture for (**a**) double-leg and (**b**) single-leg jumps. The body weight should be kept on the balls of the feet, the knees should stay flexed on landing, and the feet and knees should be kept shoulder-width apart to avoid knee hyperextension, and a valgus lower limb in collapsed position

Table 14.3 Criteria to begin Sportsmetrics advanced neuromuscular retraining

1. Normal knee stability (negative pivot-shift test, ≤3 mm increase anteroposterior tibial displacement on Lachman test or knee arthrometer test)
2. Full range of knee motion
3. ≤15% deficit peak torque hamstrings and quadriceps on isokinetic test (180°/s and 300°/s)
4. ≤15% deficit in the distance hopped between the reconstructed and contralateral legs on a single-leg hop for distance and single-leg triple hop for distance tests
5. Successful completion of running program with no pain, swelling, or giving way
6. Successful completion of basic plyometric training with therapy staff

high-risk sports activities that involve pivoting, cutting, and repetitive jumping/landing after ACL reconstruction. Whenever possible, each training session should be done under the supervision of a Sportsmetrics certified instructor (see http://sportsmetrics.org), athletic trainer, or physical therapist. Specific criteria must be met in order for a patient to begin this final phase of rehabilitation (Table 14.3). The components of the Sportsmetrics neuromuscular training program include a dynamic warm-up, plyometric jump training, strengthening, and flexibility.

During this portion of rehabilitation, the patient should continue with strengthening and other exercises as recommended by the physical therapist. Plyometrics are performed on alternating days (Monday, Wednesday, Friday), with strengthening and conditioning exercises done on the other days of the week (Tuesday, Thursday, Saturday). Training logs should be completed during each session to track the patient's progress. It is imperative that the patient masters the jumps in the current phase before entering into the next phase. This may take longer than the usual 2-week period per phase of the standard Sportsmetrics program.

If the patient does not have access to a certified Sportsmetrics instructor, then the program may be accomplished at home with the instructional videotapes (Table 14.4). The physical therapy team should be involved at the beginning of each of the three stages of Sportsmetrics training in order to instruct the patient on correct technique for the jumps.

Table 14.4 Sportsmetrics home-based program protocol

1. The physical therapist or trainer meets with patient and instructs them on the jumps in phase 1. The videotape is also used for demonstration, and further education regarding how to perform each jump and the usual corrections required
2. The patient practices the jumps during the next 7 days
3. The physical therapist or trainer and patient meet the next week and the patient demonstrates jumps. If done correctly, training begins. The patient completes phase 1 over next 2 weeks. The patient records the jumps done on the training logs for each session
4. The physical therapist or trainer and patient meet in 2 weeks. The patient must master the jumps in phase 1 before entering into phase 2. If extra time is required, this is built in according to the therapist's or trainer's recommendations
5. Upon completion of phase 2, the physical therapist or trainer teaches the patient the jumps in phase 3. The patient completes phase 3 over next 2 weeks
6. The physical therapist or trainer and patient meet 2 weeks later to determine if the patient has mastered jumps in phase 3

We have integrated both internal and external focus cues into the training strategies of Sportsmetrics in an attempt to address the neurocognitive demands of athletes. Examples of these cues are provided in this chapter (Table 14.5); a complete listing of all of these cues is available on a DVD at sportsmetrics.org. Studies conducted in our laboratory and those of others have demonstrated that the Sportsmetrics program is effective in inducing desired changes in neuromuscular indices in female athletes, including decreased peak landing forces (Fig. 14.2), decreased knee abduction/adduction moments (Fig. 14.3), increased hamstring strength, improved hamstring-to-quadriceps ratio, and improved overall lower limb alignment on a drop-jump (Figs. 14.4 and 14.5) [26, 28–33].

14.4.1 Dynamic Warm-Up

The dynamic warm-up prepares the body for rigorous training. The brief warm-up uses function-based activities that incorporate various motions of

Table 14.5 Examples of internal and external focus cues [76]

Jump	Internal focus cues	External focus cues
Squat jump	Keep shoulders back and chest lifted Hips should sit lower than shoulders and back behind the heels on the squat Keep toes, knees, and hips in line No wiggle wobble in knees Fully extend the body on the reach Land on the ball of the foot and quickly rock back to the heels going into the squat Keep head up	Position two cones in front of the athlete hip-distance apart: point knees and toes toward the cone on landing Reach hands toward the cones during the squat Reach hands toward the ceiling on every jump Pretend going to sit in a chair when coming down into the squat Imagine holding a ball between knees throughout the entire jump
Barrier jump	Land on the ball of the foot and rock back to the heel No wiggle wobble in knees Tuck the knees up to the chest Keep the knees bent on landing Keep posture tall and upright Make sure feet land at the same time Keep feet and knees hip-distance throughout each phase of the jump Focus eyes upward The entire body should travel over the cone as a unit	Position two cones in front of the athlete hip-distance apart (on each side of the barrier for side-to-side jumps or in front of barrier on forward–backward jumps): point knees and toes toward the cone on landing Tuck the knees to clear the barrier Imagine a ball being held between the knees to maintain neutral alignment
Broad jump	Keep hips, knees, and ankles in line (hip-distance) as you take off and land Stay low in landing with shoulders up and hips lower than shoulders Land on the balls of the feet and quickly rock back to the heels Look up No wobbly knees	Imagine a ball in between the legs during entire jump to maintain hip-distance Position two cones in front of the athlete hip-distance apart: point knees and toes toward the cone on landing Use cones as a goal to jump to Imagine sitting in a chair in order to stay low in landing Reach down toward the cone to lower the body into a squat position Focus eyes upward toward the instructor
Single-leg hop	Keep hip, knee, and ankle neutral Do not allow the knee to cave inward Land on the ball of the foot and rock back to heel Keep eyes focused upward Get low into a squat on landing Hips shift back and sit low, back is upright, shoulders should be higher than hips	Quiet landing, land light as a feather Position a cone a few feet in front of the athlete: point knee and toe toward a cone Use cone as goal for hop distance Look up at the instructor On landing, imagine sitting in a chair on one leg

the extremities and core to raise core body temperature, increase heart rate, increase blood flow to the muscles, and improve balance and coordination. The exercises are performed across the width of a court or field or for approximately 20–30 s.

14.4.1.1 Toe Walk

Walk on the toes and keep the legs straight (Fig. 14.6). Do not allow the heel to touch the ground. Keep the hips neutral during the entire exercise.

14.4.1.2 Heel Walk

Walk on the heels and keep the legs straight (Fig. 14.7). Do not allow the toes to touch the ground. Do not lock the knees, but keep them slightly flexed. Keep the hips neutral during the entire exercise.

14.4.1.3 Straight Leg March

Walk with both legs straight, alternating lifting up each leg as high as possible without compromising form (Fig. 14.8). Keep the knees

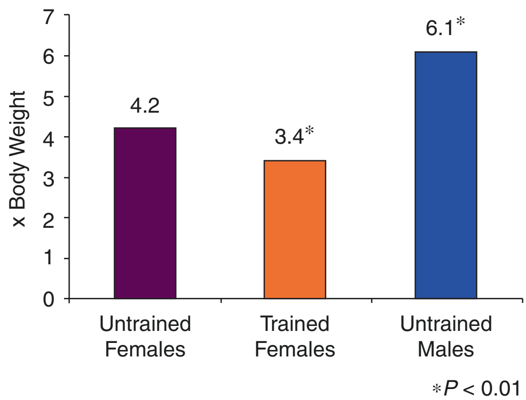


Fig. 14.2 Peak landing forces in 11 female subjects before and after Sportsmetrics training and in 9 male control subjects. There was a significant difference between untrained females and trained females, and between males and both female groups ($P < 0.01$). These forces decreased an average of 456 N (103 pounds) after training, which represented a decrease of 22% in the peak landing force ($P = 0.006$) [26]

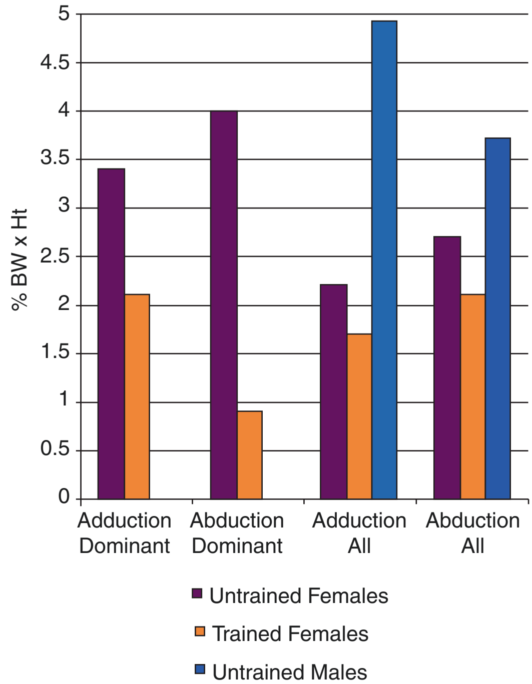


Fig. 14.3 Peak knee adduction and abduction moments on landing from a vertical jump before and after Sportsmetrics training. The female subjects were grouped according to the dominant moment (adduction or abduction) and were also grouped together (All). In the dominant subgroups, the trained females had significantly smaller adduction and abduction moments compared to the untrained females ($P < 0.05$). Peak abduction and abduction moments were significantly greater in the male subjects than those in the trained female subjects ($P < 0.05$) [26]

straight and the posture erect. Do not lean backward.

14.4.1.4 Leg Cradle

Walk forward and keep the entire body straight and neutrally aligned. Lift one leg off the ground in front of the body, bending at the knee (Fig. 14.9). Turn the knee outward and grasp the foot with both hands. Hold this position for 3 s, and then place the foot back down and repeat with the opposite leg.

14.4.1.5 Dog and Bush (Hip Rotator) Walk

Pretend there is an obstacle directly in front of you. Face forward and keep the shoulders and hips square. Extend one leg at the hip and keep the knee bent (Fig. 14.10). Rotate the leg out at the hip and bend the knee to 90°. Rotate and bring the leg up and over the obstacle, and then place it back on the ground. Repeat with the opposite leg.

14.4.1.6 High Knee Skip

This exercise involves skipping in which one knee is driven up in the air as high as possible, while the other is used to land and hop off the ground. Immediately, repeat the skip on the opposite side with each land. Swing the arm opposite of the high knee up in the air to help gain height.

14.4.1.7 High Knees

This exercise involves jogging where, with each step, the knees are driven up as high as possible using short, choppy steps. The shoulders and hips are kept square throughout the exercise.

14.4.1.8 Glut Kicks

This exercise involves jogging where, with each step, the athlete kicks the feet back as if trying to reach the gluts with the heel, using short, choppy steps. The shoulders and hips are kept square throughout the exercise.

Fig. 14.4 The video drop-jump take-off sequences from a 14-year old female basketball player before and after neuromuscular training. (**a**) Before training, the athlete demonstrated poor absolute knee separation distance of 17 cm. (**b**) After training, a marked improvement in knee separation distance of 37 cm is evident (reprinted from Noyes et al. [32])

14.4.1.9 Stride Out

Begin jogging forward using an exaggerated running form. Drive the knees as high as possible and kick the feet back, as if trying to make a large complete circle with the legs. Stay up on the balls of the feet throughout the exercise.

14.4.1.10 All-Out Sprint

Sprint forward as fast as possible, making sure to maintain the proper technique and running form.

14.4.2 Plyometrics/Jump Training

The philosophy regarding this component of the Sportsmetrics program is to emphasis and teach correct jumping and landing techniques throughout the 6 weeks of training. Plyometrics may enhance muscular power, vertical jump height, acceleration speed, and running speed [34–38] However, if done improperly, these exercises are not be expected to have a beneficial effect in reducing the risk of a noncontact ACL injury. Therefore, specific drills and instruction using internal and external focus cues are employed to train the athlete to preposition the entire body safely when accelerating into a jump and when decelerating on landing. The exercises progress from simple jumps (to instill correct form) to multidirectional, single-foot hops and plyometrics with an emphasis on quick turnover (to add movements that mimic sports-specific motions).

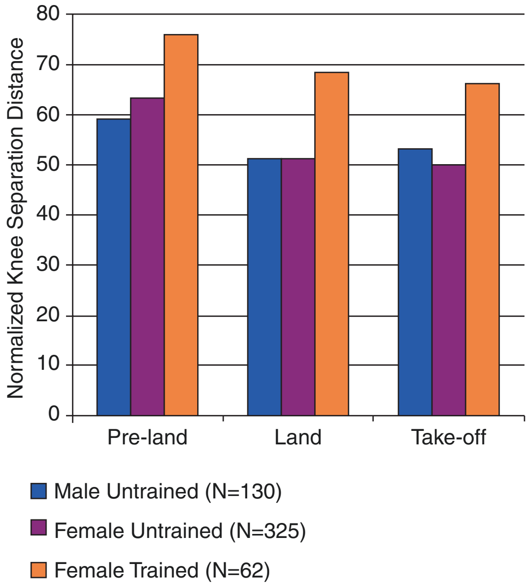


Fig. 14.5 The mean normalized knee separation distances for the three phases of the drop-jump test are shown for 130 male athletes, 325 untrained female athletes, and 62 trained female athletes. After training, female athletes had statistically significant increases in the mean normalized knee separation distance in all three phases ($P < 0.001$) and had statistically greater mean normalized knee separation distances than males for all phases ($P < 0.0001$) (reprinted from Noyes et al. [32])

The jump training is divided into three 2-week phases, each of which has a different training focus and exercises (Table 14.6).

Phase 1 (technique development phase) focuses on the accurate form and technique for eight jumps. This involves correct posture and body alignment throughout the jump, whereby the spine is kept erect, the shoulders back, and the chest over knees. Athletes are encouraged to jump straight up and land straight down with no excessive side-to-side or forward–backward movement. Soft landings using toe-to-heel rocking and flexed knees are critical components to the initial instruction of the jumps. Verbal queues include “on your toes”, “straight as an arrow”, “light as a feather”, “shock absorber”, and “recoil like a spring”. Constant feedback is offered by instructors. The jumping exercises are gradually increased in duration or repetition. If the athlete becomes fatigued or cannot perform the jumps with the proper technique, they are encouraged to stop and rest. Approximately 30 s of recovery time is allowed between each exercise.

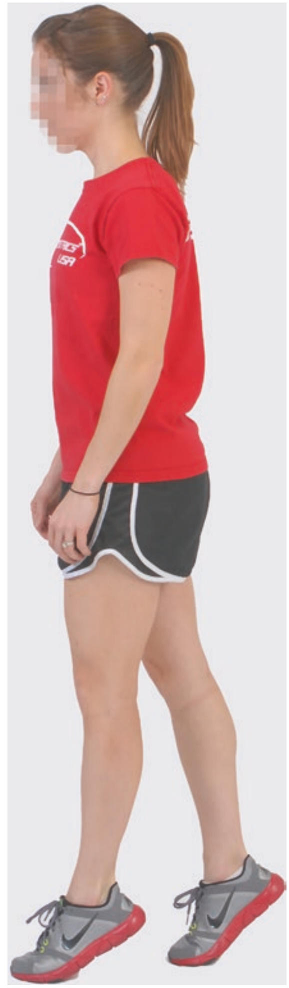


Fig. 14.6 Toe walk [76]

Phase 2 (fundamentals phase) continues emphasis on proper techniques. Athletes continue to perform six of the jumps from phase 1, but for longer periods of time. In addition, three new jumps are incorporated. Phase 3 (performance phase) increases the quantity and speed of the jumps to develop a truly plyometric exercise routine. The athlete completes as many jumps as possible with proper form and is encouraged to focus on the height achieved in each jump.

Fig. 14.7 Heel walk [76]

14.4.2.1 Wall Jump

Instruction This jump is always performed first to prepare the athlete mentally and physically for training. The instructor observes and begins positive feedback and instruction. Raise both arms overhead and jump with minimal knee flexion and maximal ankle flexion, landing softly. On each landing, the hips, knees, and ankles should be in neutral alignment, the back straight, the head up, and the eyes looking straightforward.

Common Problems Slouched posture, excessive knee flexion, head down, eyes watching the feet.

Fig. 14.8 Straight leg march [76]

Corrections Keep the eyes and head focused up, keep the knees slightly bent, land softly.

14.4.2.2 Tuck Jump

Instruction Begin standing with the feet shoulder-width apart. Jump up and bend the knees upward together up toward the chest as high as possible (Fig. 14.11) Land softly with the knees slightly flexed and feet shoulder-width apart.

Common Problems Lowering the chest to the knees rather than lifting the knees to the chest, bringing the knees together during take-off or landing, double-bouncing between jumps, and landing loudly with a lack of muscle control.

Corrections Lift the knees up to the chest, keep the landing controlled and soft, land on the balls of the feet, keep the knees and ankles at shoulder-width

Fig. 14.9 Leg cradle [76]

throughout the jump, the back should be straight, and the eyes looking up.

14.4.2.3 Squat Jump

Instruction Start in a fully crouched position as deep as comfortable with the hands touching the ground on the outside of the heels. Point the knees and feet forward and keep the upper body upright with the chest open. Jump up and raise the arms to reach as high as possible, and then return to the starting position with hands reaching back toward the heels.

External Focus Cue Position two cones in front of the athlete hip-distance apart and instruct the athlete to point their knees and toes toward the cone on landing (Fig. 14.12).

Common Problems Landing with body or knees forward, being off-balance, bringing the knees together during take-off or landing, and landing loudly with a lack of control.

Corrections Reach the hands back toward the heels, keep the knees under the hips on take-off and landing, keep the knees and ankles shoulder-width apart, keep the back straight, and the head and eyes up.

14.4.2.4 Barrier Jump Side-to-Side

Instruction A cone or barrier approximately 6–8 inches (in; 15.24–20.32 cm) in height is placed on a hard surface. Start upright with the knees deeply flexed and then jump from one side of the barrier to the other, keeping the feet together. Land on both feet at the same time, with the same amount of knee flexion as the starting position.

External Focus Cue Position two cones in front of the athlete hip-distance apart and instruct the athlete to point their knees and toes toward the cone on landing (Fig. 14.13).

Common Problems Starting or landing with stiff, straight, or wobbly knees; not bringing the entire body over the barrier; double-bouncing on landing and take-off; and not landing with the feet together.

Corrections Bend the knees up to clear the barrier, land softly on the balls of the feet and rock back to the heels, control the landing to be able to immediately take off again, keep the back straight with the shoulders back, and keep head and eyes up with each jump.

14.4.2.5 Barrier Jump Forward–Backward

This is the same as the barrier jump side-to-side, except that the athlete jumps forward and backward over the barrier.

14.4.2.6 180° Jump

Instruction Begin with the knees slightly flexed and the feet shoulder-width apart. Jump straight up and turn 180° in midair before landing (Fig. 14.14). Hold the landing for 2–3 s, and then reverse the direction and repeat the jump.

Fig. 14.10 (**a**, **b**) Dog and bush walk [76]

Common Problems Rotating too much or too little; not completing an entire 180° turn; not rotating the body together as a unit; landing loudly with straight, stiff-legged knees, or with staggered feet or one foot landing before the other; always jumping in the same direction (in a circle); achieving only minimal height during jump; and not keeping the feet shoulder-width apart on landing.

Corrections Jump straight up and rotate the body as a unit from the head to the toes, land softly with the knees slightly flexed, alternate each jump toward the opposite direction (one jump over the right shoulder, the next over the left), keep the knees and ankles at shoulder-width, keep the back straight, and keep the head and eyes up.

14.4.2.7 Broad Jump

Instruction Begin with the knees deeply flexed, then jump forward as far as possible, taking off and landing on both feet at the same time. Land softly in the same deeply crouched position, hold for 5 s, and then repeat the jump.

External Focus Cue Position two cones in front of the athlete hip-distance apart and instruct the athlete to point their knees and toes toward the cone on landing and use them as a goal to reach (Fig. 14.15).

Common Problems Not holding or sticking the landing, letting the knees collapse inward during landing and take-off, landing with little knee

Table 14.6 Sportsmetrics neuromuscular training program: jump training component [76]

Jumps	Duration	
Phase 1: technique	Week 1	Week 2
Wall jump	20 s	25 s
Tuck jump	20 s	25 s
Squat jump	10 s	15 s
Barrier jump (side-to-side)	20 s	25 s
Barrier jump (forward–back)	20 s	25 s
180° jump	20 s	25 s
Broad jump (hold 5 s)	5 reps	10 reps
Bounding in place	20 s	25 s
Phase 2: fundamentals	Week 3	Week 4
Wall jump	25 s	30 s
Tuck jump	25 s	30 s
Jump, jump, jump, vertical jump	5 reps	8 reps
Squat jump	15 s	20 s
Single-leg barrier hop side-to-side[a]	25 s	30 s
Single-leg barrier hop forward–back[a]	25 s	30 s
Scissors jump	25 s	30 s
Single-leg hop[a] (hold 5 s)	5 reps	5 reps
Bounding for distance	1 run	2 runs
Phase 3: performance	Week 5	Week 6
Wall jump	25 s	20 s
Jump up, down, 180°, vertical	5 reps	10 reps
Squat jump	25 s	25 s
Mattress jump side-to-side	30 s	30 s
Mattress jump forward–back	30 s	30 s
Single-leg hop, hop, hop, stick[a]	5 reps	5 reps
Jump into bounding	3 runs	4 runs

[a]Repeat on both sides for the duration or repetitions listed.

flexion or in an upright position, and using a slouched posture.

Corrections Keep the knees over the heels and under the hips on take-off and landing, land softly on the balls of the feet and rock back to the heels, and land in control with the knees deeply flexed.

14.4.2.8 Bounding in Place

Instruction Begin by standing on one leg with the knee slightly flexed, eyes looking straight ahead, and the opposite leg bent behind the body. Staying in one place, alternate the leg positions by driving the back leg forward and upward (Fig. 14.16). Progressively increase the rhythm and height throughout the exercise.

Common Problems Simply alternating the knees or jogging in place, landing loudly, and landing with unstable knees.

Corrections Use the arms to countermove the legs in order to increase height and power, drive the knees upward, and land softly.

14.4.2.9 Jump, Jump, Jump, Vertical Jump

Instruction The exercise begins with three consecutive broad jumps, using deep knee flexion for each take-off and landing. Immediately after landing the third jump, a maximum vertical jump is performed and then the deep crouch position is used for the final landing, which is held for 5 s.

Common Problems Allowing the knees to collapse inward during landing and take-off, and carrying the body forward rather than up on the vertical jump.

Corrections Keep the knees over the heels and under the hips on take-off and landing, land with the knees deeply flexed on the balls of the feet and rock back to the heels, and go straight up on the vertical jump.

14.4.2.10 Barrier Hop Side-to-Side, Single Leg

Using the same cone or barrier from phase 1, a single-leg hop side-to-side over the barrier is performed.

14.4.2.11 Barrier Hop Forward–Backward, Single Leg

Using the same cone or barrier from phase 1, a single-leg hop forward and backward over the barrier is performed (Fig. 14.17).

14.4.2.12 Scissor Jump

Instruction Begin in a lunge position with the front knee bent directly over the ankle. Push off with the front leg, jump straight up in the air (Fig. 14.18), and land with the opposite leg bent in front. Alternate the legs with each jump.

Fig. 14.11 (**a**, **b**) Tuck jump [76]

Fig. 14.12 Squat jump with external focus cue [76]

Common Problems Landing with unstable knees or with the front knee extended past the ankle, alternating legs with minimal height, not switching the legs directly under the body, landing loudly, landing with a straight knee, or landing with staggered feet.

Corrections Push off using the front leg for power, land in control with the legs bent and the front knee directly over the ankle, keep the back straight, keep the head and eyes up, and keep the toes pointed forward.

14.4.2.13 Single-leg Hop

Instructions This hop is similar to the broad jump, except that the athlete begins and lands on one leg. The landing in a deep crouched position is held for 5 s.

External Focus Cue Position a cone a few feet in front of the athlete and instruct the athlete to point their knee and toes toward the cone on landing and use it as a goal to reach (Fig. 14.19).

Fig. 14.13 (**a**–**c**) Barrier jump side-to-side with external focus cue [76]

Common Problems Landing with an unstable or straight knee and landing in deep knee flexion but standing up immediately.

Corrections Take-off and land with the knees and ankles flexed; holding the landing for 5 s is more important than the distance jumped.

14.4.2.14 Bounding for Distance

Instructions Begin bounding in place as described for weeks 1–2 and then progress in a forward direction. Increase the distance with each step and keep the knees high.

Common Problems Performing alternating knee lifts or a high knee jog, landing loudly or with unstable knees, and keeping the knee too low.

Corrections Use the arms to countermove the legs in order to increase height and power, drive the knees upward, and land softly.

14.4.2.15 Jump Up, Down, 180°, Vertical

Instructions Begin by flexing both knees and jumping onto a 6–8” box or stacked mat. Land with both feet together in a deep crouched position and immediately jump down off the box or mat. Land again in a deep crouched position and immediately perform a 180° jump, followed by a maximum vertical jump, landing in the deep crouched position which is held for 5 s.

Common Problems Landing in an upright straight or stiff-legged stance or landing with the feet staggered.

Fig. 14.14 (**a**–**c**) 180° jump [76]

Fig. 14.15 (**a**, **b**) Broad jump with external focus cue [76]

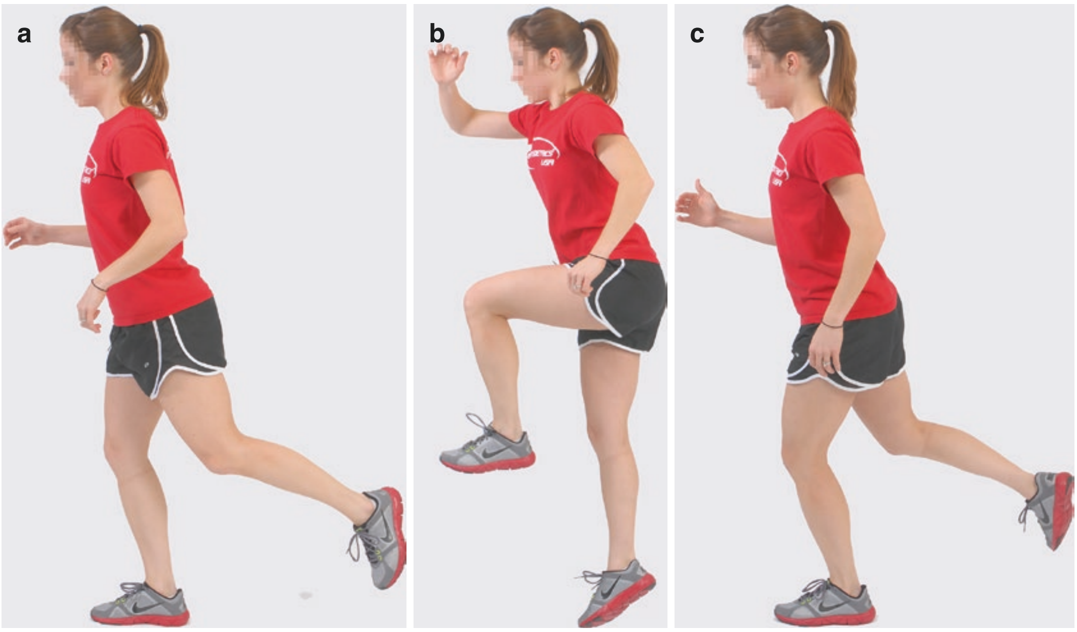


Fig. 14.16 (**a**–**c**) Bounding in place [76]

Fig. 14.17 (**a**–**c**) Barrier hop forward–backward [76]

Fig. 14.18 (**a**–**c**) Scissor jump [76]

Corrections Land every jump in a deep crouch with the knees and ankles flexed, and take-off and land on both feet at the same time.

14.4.2.16 Mattress Jump Side-to-Side

Instructions A cone or barrier is placed on a cushioned surface approximately 2–3 in. (5.08–7.62 cm) deep. Jump from one side to the other over the barrier (Fig. 14.20).

Common Problems Landing with unstable knees or knees collapsed inward, double-bouncing on landing, and landing with the feet staggered.

Corrections Take-off and land with both feet parallel and together, and control the landing to be able to immediately take-off back over the barrier.

14.4.2.17 Mattress Jump Forward–Backward

This jump is the same as the mattress jump side-to-side, except the jump is performed forward and backward over the barrier.

14.4.2.18 Hop, Hop, Hop, Stick

Perform three single-leg hops for a distance and hold the final landing for 5 s. The common problems and corrections are those described for the single-leg hop.

14.4.2.19 Jump into Bounding

Jump forward off both feet, land on one leg with the other bent behind, and immediately begin bounding for distance. The common problems and corrections are those described for the bounding for distance hop.

Fig. 14.19 (**a**, **b**) Single-leg hop with external focus cue [76]

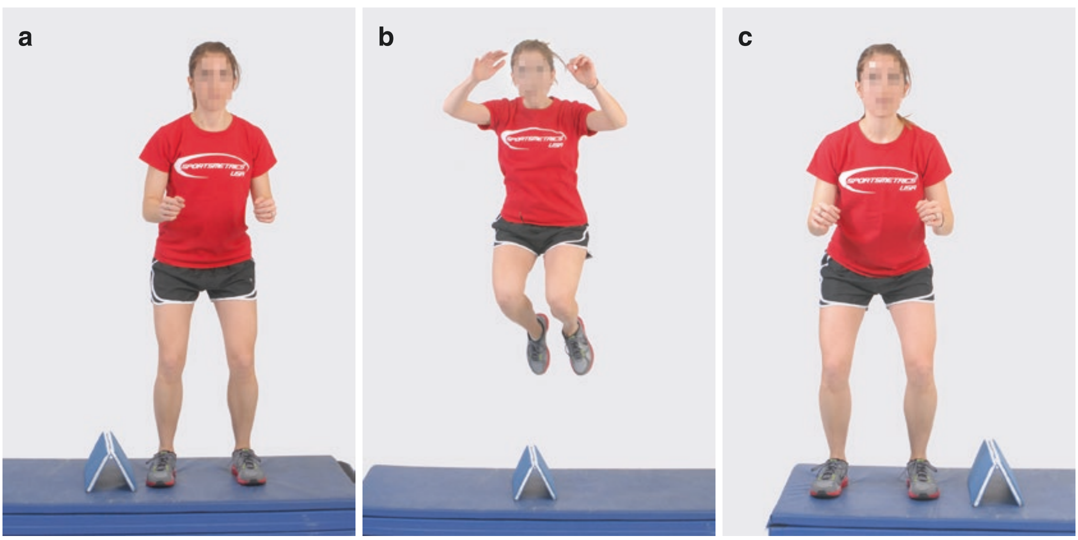


Fig. 14.20 (**a**–**c**) Mattress jump side-to-side [76]

14.4.3 Strength Training

A combination of exercises is recommended to develop upper extremity, lower extremity, and core to improve the overall muscular efficiency. Either weight equipment or free weights may be used based on the available facilities. The lower extremity muscle groups targeted are the quadriceps, hamstrings, gluteals, and gastrocnemius. The athlete begins with 12 repetitions for each muscle group. When 15 repetitions can be performed, the amount of weight is increased. The upper body muscle groups are the deltoids, pectorals, triceps, latissimus dorsi/low back, and abdominals. Ten repetitions are recommended initially, and when the athlete can perform 12 repetitions, the amount of weight is increased. Athletes are encouraged to use 70% of their one-repetition maximum when beginning strength training. The overload principle is stressed. When strength training equipment is available, the following exercises are recommended: leg press, leg curl, calf raises, seated row, chest press, latissimus dorsi pull-down, shoulder raises, back hyperextension, and abdominal crunches. For athletes who do not have access to weight equipment, exercises using body weight and resistance band may be used as described below.

14.4.3.1 Mini-Squats with Resistance Band

Instructions Stand on the center of a strip of resistance band with the feet shoulder-width apart (Fig. 14.21) and grip each end of the band. Pull both hands up to waist level to make the band tight. Squat down to an approximate 70° bend at the hips and knees, lowering the body against the resistance of the band. Keep the knees over the ankles. Push through the heels and rise up to the starting position. Perform for 30 s during weeks 1–3 and 60 s during weeks 4–6.

Common Problems Forward shift of the body or knees, using a slouched posture, and maintaining too much slack in the band.

Corrections Wiggle the toes throughout the exercise, keep the back straight, the head up with eyes looking forward, and the knees centered over the ankles.

Fig. 14.21 (**a**, **b**) Mini-squat with resistance band [76]

14.4.3.2 Walking Lunges Forward

From a standing position, step out with one leg as far as possible. Bend the knees and lower the back leg toward the ground, stopping just before the knee touches the ground (Fig. 14.22). Keep the front knee over the ankle. Use the front leg to lift back up to the standing position. Bring the back leg alongside the front leg, pause, and repeat with the opposite leg. Perform for 30 s in weeks 1–3 and 60 s in weeks 4–6.

14.4.3.3 Prone Hamstrings with Partner Resistance

Instructions The athlete performing the exercise lies flat on a mat on their stomach with the abdominal and gluteus muscles tightened to press the hips into the floor. A partner uses their hands to place pressure on the lower calf which the athlete resists, bending at the knee so that the heel comes toward the gluteus muscles without raising the hips off the mat. The athlete continues to bend and straighten the leg as the partner applies pressure. Perform on each leg for 30 s during weeks 1–3 and 60 s during weeks 4–6.

Fig. 14.22 Lunge with external focus cue [76]

Common Problems The upper body or working hip lifts off the ground, and the partner does not provide enough resistance to create eccentric contractions.

Corrections The hips are kept pressed into the ground, the upper body relaxed, and the leg is moved through the full range of motion.

14.4.3.4 Supine Hamstring Bridge

Instructions Lie flat on the back, bend one knee, and place the heel of the foot as close to the gluteus as possible. Extend the other leg straight up into the air (Fig. 14.23). Push through the heel of the foot that is on the ground and perform small lifts in which the gluteus is raised off the ground by moving the extended leg higher in the air with each lift. Keep the abdominals tight and the upper back in neutral. Perform on each leg for 30 s during phase 1.

Common Problems The leg is simply swung in the air back and forth, the gluteus is not raised off the ground, the leg in the air is bent, the toe is used to push and not the heel, and the body is held up off the ground with the arms or hands.

Corrections Press through the heel, keep the abdominals tight and the lower back straight, lift the leg in the air straight up, and raise and lower the leg slowly and under control.

14.4.3.5 Bridge with Alternating Leg Hamstring Glide

This exercise is similar to the supine hamstring bridge; however, both heels are placed as close as possible to the gluteus. Slide one leg to near full extension, keeping the heel on the ground, and then return it to the starting position. Perform on each leg for 30 s in phase 2.

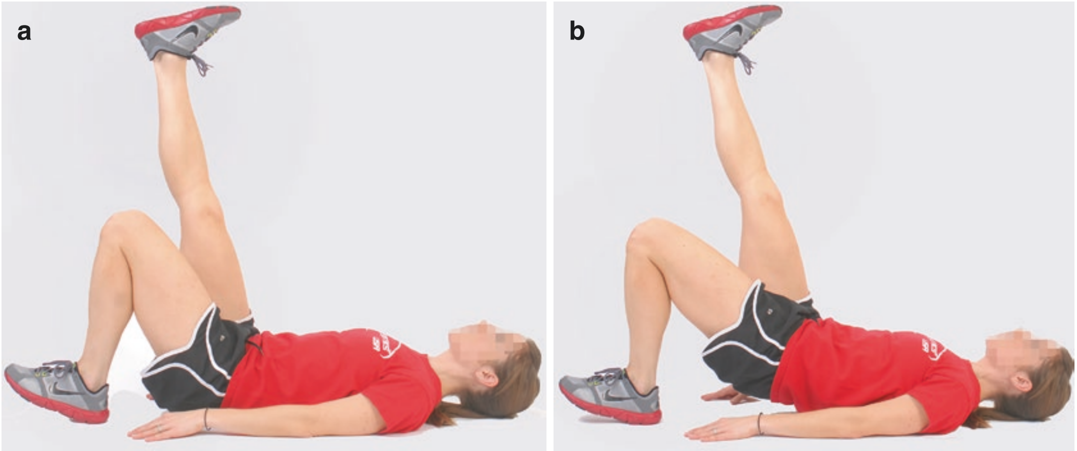


Fig. 14.23 (**a**, **b**) Supine hamstrings bridge [76]

14.4.3.6 Bridge with Double-leg Hamstring Glide

This exercise is similar to the alternating leg hamstring glide; however, both legs are slid together to near full extension and then brought back to the starting position. Perform for 30 s in phase 3.

14.4.3.7 Arm Swing with Resistance Band

Instructions Stand on the center of a strip of resistance band with the feet shoulder-width apart and grip each end of the band. Pull the resistance band to waist level so that the band is tight and the elbows are at a 90° angle (Fig. 14.24). Maintain this position and mimic a running pattern by alternatively swinging the arms from the hip up to the ear. Perform for 30 s during weeks 1–3 and 60 s during weeks 4–6.

Common Problems The arms are not kept at a 90° angle through the full range of motion, the knees are locked, and the torso is twisted.

Corrections The head should be kept up with the eyes looking straight ahead, the shoulders should be back, the back neutral, and the abdominals tight.

14.4.3.8 Superman (Alternating Arms/Legs)

Instructions Lie face down and place the forehead on top of the back of one hand. Extend the other arm out on the ground. Tighten the abdominal muscles and raise the upper body in order to lift the extended arm. Simultaneously, raise the leg opposite from the extended arm using the hip and gluteals (Fig. 14.25). Extend the toes and fingers on the lifted extremities and keep the abdominals tight. Perform for 30 s during weeks 1–3 and for 60 s during weeks 4–6.

Common Problems The head is lifted up, the back is excessively arched, and the leg is raised to the side.

Corrections Keep the back as neutral as possible and focus the eyes on the mat or ground directly below. Lift up from the trunk and lift the leg and arm only to where tension is felt in the lower back. Keep the abdominals tight.

14.4.3.9 Abdominals (Russian Twists)

Instructions Lie on the ground, bend the knees, and place the heels on the floor. Raise the upper body up to a 45° angle by bending at the hips and not the waist. Maintain this position and move the trunk as a unit to rotate the upper body side-to-side. Touch the ground with the hands next to the hip with each rotation (Fig. 14.26). Perform 1 day each week for 30 s in phase 1, 60 s in phase 2, and 90 s in phase 3.

Fig. 14.24 (**a**, **b**) Arm swing with resistance band [76]

Fig. 14.25 Abdominals (Superman) [76]

Common Problems The posture is slouched with rounded shoulders. Only the shoulders are twisted instead of the entire torso.

Corrections Keep the back straight and shoulders relaxed and the upper body at a 45° angle. Move the torso as a unit and touch the ground with the hands with each rotation.

14.4.3.10 Abdominals (Plank)

Instructions Lie face down and position the elbows under the shoulders with the forearms on the floor (Fig. 14.27). Place the legs hip-distance apart and curl the toes. Lift the body up onto the elbows and toes, tighten abdominals, and hold. Perform 1 day each week for 30 s in phase 1, 60 s in phase 2, and 90 s in phase 3.

Common Problems The back or midsection is slouched or arched, the head is placed down and the chin rests on the chest, and the elbows and/or toes are kept too close together.

Corrections Keep the head and posture in a neutral position and the body in a straight line parallel to the ground. Tighten the abdominals throughout the exercise.

14.4.3.11 Abdominals (Bicycle Kicks)

Instructions Lie on the back and bend both knees toward the chest. The fingertips are positioned either on the back of the ears or crossed over the chest. Raise the upper body up until the shoulders no longer touch the ground. Hold this position and move the legs in a cyclic motion, bringing the heels into the gluteus and extending the legs out as close to the floor as

Fig. 14.26 (**a**, **b**) Abdominals (Russian twists) [76]

Fig. 14.27 Abdominals (plank) [76]

Fig. 14.28 (**a**, **b**) Abdominals (bicycle kicks) [76]

possible (Fig. 14.28). Perform 1 day each week for 30 s in phase 1, 60 s in phase 2, and 90 s in phase 3.

Common Problems The shoulders are not kept off of the ground, the upper body rotates, and the legs are moved close to body.

Corrections Lift the upper body up from the waist, keep the elbows open and upper body stationary, and take the legs through a full cycle close to the ground.

14.4.3.12 Hip Flexor Resistance Band Kicking

Instructions Place one end of a piece of resistance band around the ankle and the other end around a stationary object. Stand with the back to the stationary object and then step forward with the free leg to produce moderate tension in the band, producing approximately 15° of hip extension in the leg with the resistance band (Fig. 14.29). Then, drive the knee up and forward with maximal effort against the resistance of the band until the thigh is parallel with the ground. Return the leg to a slightly extended position after each exertion. Perform two sets of 10 repetitions, with 30 s of rest between each set. A third set of 20 repetitions is done in phase 1, 30 repetitions in phase 2, and 40 repetitions in phase 3.

Common Problems The leg to be exercised is simply swung up and back, the hip is hiked up, and the torso moves.

Corrections Keep the head and neck straight and the upper body still, keep the shoulders and hips square, and return the exercising leg to a slightly extended position before kicking forward again.

14.4.3.13 Steamboats (Hip Flexion)

Instructions This exercise may be done in place of hip flexor resistance band kicking. Place a resistance band just above the ankles (Fig. 14.30). Begin with the feet shoulder-width apart, with one knee slightly bent so that the foot is off the ground.

Fig. 14.29 (**a**, **b**) Hip flexor resistance band kicking [76]

Balance on the other leg and kick the bent leg forward and backward at the hip. Keep the upper body stationary. Perform for 30 s on each leg during weeks 1–3 and 60 s during weeks 4–6.

Common Problems Bending or extending the knee and not moving at the hip, swaying the upper body back and forth, and not kicking hard enough to feel the resistance from the band.

Corrections Keep the back straight, the shoulders back, and the head and eyes up. There should be a small bend in both knees at all times. The upper body is kept still and the hips level.

14.4.3.14 Hip Abductor Resistance Band kicking

Instructions Place one end of a piece of resistance band around the ankle and the other end around a stationary object. Stand sideways so that the leg with the resistance is furthest away from the object (Fig. 14.31). Step far enough to produce moderate tension in the band and then kick the outside leg sideways against the resistance of the band. Perform two sets of 10 repetitions, with 30 s of rest between sets. A third set of 20 repetitions is done in phase 1, 30 repetitions in phase 2, and 40 repetitions in phase 3.

Common Problems The leg is swung out and back without control, and the upper body leans too far forward or sideways while kicking.

Corrections Keep the head and neck straight and the upper body still. Look straight ahead and keep the shoulders and hips square.

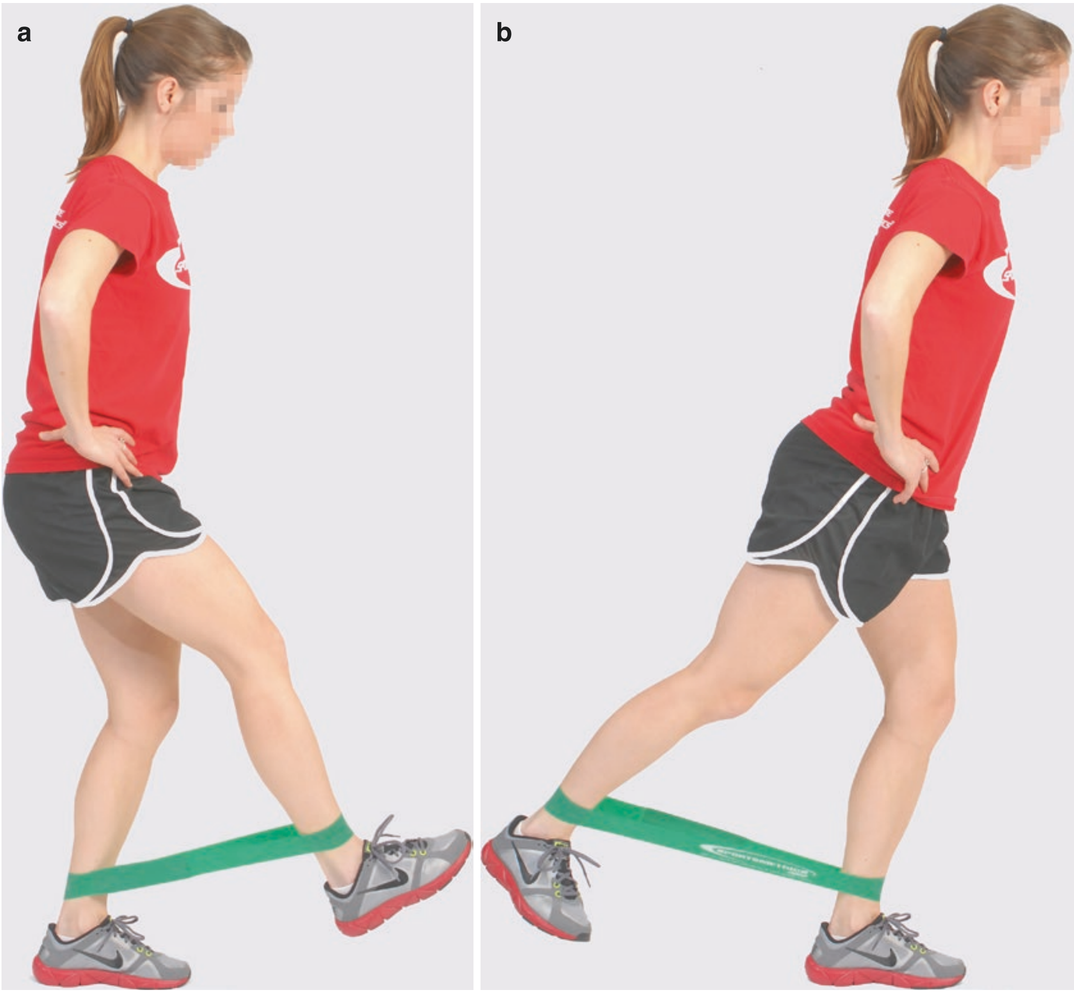


Fig. 14.30 (**a**, **b**) Steamboats [76]

14.4.3.15 Lateral Walking with Resistance Band

Instructions This exercise may replace hip abduction resistance band kicking. A resistance band is positioned just above the ankles (Fig. 14.32). Begin with the feet shoulder-width apart. Step out with one foot 2–3 feet to the side. Slowly and under control, bring the other foot up to assume the feet shoulder-width apart position. When the distance walked is finished, reverse directions so that the opposite foot leads the exercise. Perform for 30 s during weeks 1–3 and 60 s during weeks 4–6.

Common Problems Allowing the feet come together between steps, snapping the leg that follows back to the starting position, keeping the knees locked, bending forward at the waist, rounding the shoulders, and looking down at the ground.

Corrections Keep the back and shoulders straight and the head and eyes up. Use a comfortable distance between steps that permits leg control throughout the exercise and keep the walking motion slow and under control at all times.

Fig. 14.31 (**a**, **b**) Hip abductor resistance band kicking [76]

14.4.4 Flexibility

Stretching exercises are important to achieve the maximum muscle length to allow muscles to work with power through a complete range of motion. Passive flexibility exercises are performed at the conclusion of training, with each stretch held for 20–30 s and repeated two times on each side. The major muscle groups targeted are the hamstrings, iliotibial band, quadriceps, hip flexor, gastrocnemius, soleus, deltoid, triceps, biceps, pectoralis, and latissimus dorsi.

14.4.4.1 Hamstrings

Instructions Sit on the floor and extend the right leg fully. Bend the left knee and place the inside of the foot along the left calf (Fig. 14.33). Keep the back straight and slowly reach with both hands toward the toes. Place the hands on the floor along the side of the legs or hold onto the toes.

Common Problems The shoulders are rounded when leaning into the stretch, the head drops and the chin rests on the chest, and the knee of the leg on the ground bends.

Corrections Keep the back straight when leaning forward, bend forward at the waist, and keep the shoulders back and head up.

14.4.4.2 Iliotibial Band

Sit on the floor, bend the right knee, and place the right foot flat on the floor. Put the left foot and ankle on the right thigh just above the knee. Place both hands on the floor behind the hips

Fig. 14.32 (**a**, **b**) Lateral walking with resistance band [76]

Fig. 14.33 Hamstrings stretch [76]

Fig. 14.34 Iliotibial band stretch [76]

and press the chest toward the knee and foot. Keep the upper torso, neck, and shoulders neutral and open and do not allow the upper back to become rounded (Fig. 14.34). This stretch may be done lying on the back to support the spine and neck.

14.4.4.3 Quadriceps

Instructions From a standing position, grab a foot or ankle and lift it up behind the body. Gently pull the lower leg and foot up, directly behind the upper leg. Do not twist inward or outward (Fig. 14.35).

Fig. 14.35 Quadriceps stretch [76]

Common Problems Resting the foot on the buttocks, pulling the leg and/or foot inward or outward, and locking the knee of the leg used for balance.

Corrections Pull the foot straight up, keep the back straight, the shoulders back, and the head up.

14.4.4.4 Hip Flexor

Instructions Begin in a lunge position with the front knee slightly bent (Fig. 14.36). Push up on the rear toe, press the hips forward, and tighten the buttocks until a stretch is felt in the front of the hip. Keep the upper torso upright and centered directly over the hips.

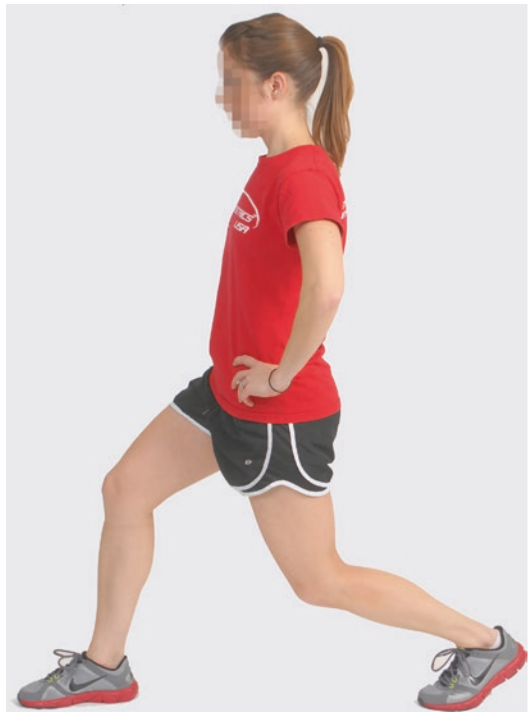


Fig. 14.36 Hip flexor stretch [76]

Common Problems The upper body leans forward and the hips are not pressed forward.

Corrections Keep the torso upright and centered over the hips, press or rock the hips forward, and keep the back straight, shoulders back, and head up.

14.4.4.5 Gastrocnemius

Instructions Begin in a long lunge position with the front knee slightly bent, but not extended past the ankle (Fig. 14.37). Place both hands on the front of the thigh and lean the body forward while keeping the back leg straight. Press the back heel down. This stretch may also be done by assuming the same position, but the hands are placed against a wall for support.

Fig. 14.37 Gastrocnemius stretch [76]

Common Problems The back heel rises off of the ground, the knee of the back leg bends, and upper body posture is not maintained.

Corrections Keep the back leg straight and the heel on the ground. Keep the back straight, the shoulders back, and head up.

14.4.4.6 Soleus

Stand in a short lunge position. Bend both knees and sit the hips down into the back heel, with the majority of body weight on the back leg. Keep the heel on the floor. This stretch may also be done by placing both hands against a wall.

14.4.4.7 Deltoid

While either standing or sitting, bring the left arm across the body, placing the elbow close to the chest. Clasp the arm at the elbow and gently press into and across the body (Fig. 14.38). Keep the shoulders relaxed and the head and neck neutral.

14.4.4.8 Triceps, Latissimus Dorsi

While either standing or sitting, extend the right arm above the head. Bend the elbow behind the head and bring the palm of the hand toward the center of the upper back. Grasp the elbow with the left hand and gently press down and back (Fig. 14.39).

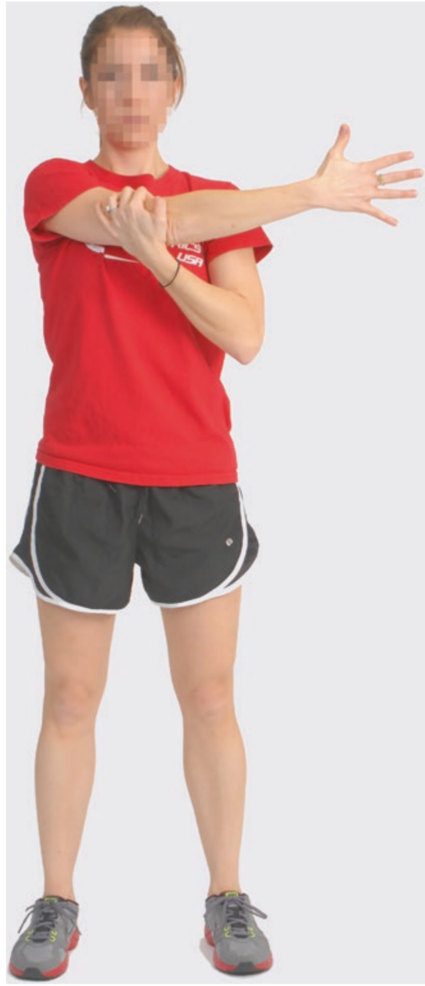


Fig. 14.38 Deltoid stretch [76]

14.4.4.9 Pectoralis, Biceps

While standing, clasp the hands behind the back. With the shoulders and neck relaxed, extend the elbows. Keep the chest open and lift the hands up. The posture stays upright and neutral and the knees slightly flexed (Fig. 14.40).

14.4.4.10 Low Back

Kneel on the floor with the hands close to the buttocks. Bend forward with the arms fully extended reaching out onto the floor. Lower the head between the arms with the forehead close to or resting on the floor. Gradually move the hands

Fig. 14.39 (**a**, **b**) Triceps, latissimus dorsi stretch [76]

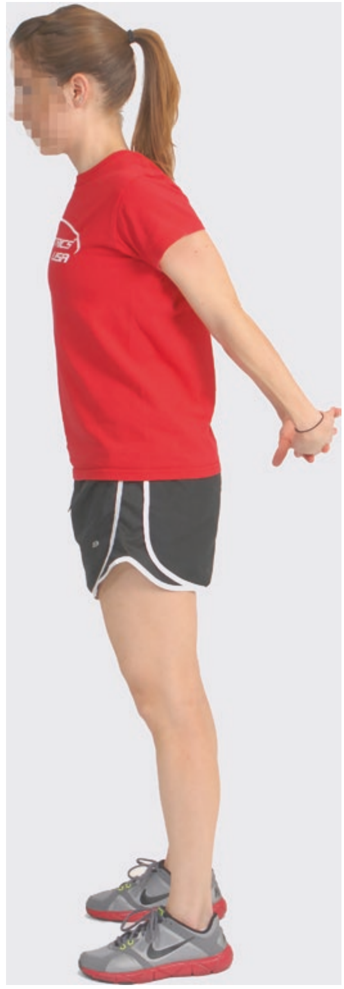


Fig. 14.40 Pectoralis, biceps stretch [76]

Fig. 14.41 Low back stretch [76]

further away from the body. Do not rise up from the heels (Fig. 14.41).

14.5 Release to Unrestricted Sports Activities

Release to unrestricted sports activities is based on the successful completion of the plyometric programs and the criteria shown in Table 14.7 [19, 39]. Testing includes KT-2000 [40, 41] and other physical examination parameters: quadriceps and hamstrings isokinetic [42–52], isometric [53–55], or one-repetition maximum bench press and leg press [56, 57]; two single-leg hops [42, 44, 45, 58–62]; video drop-jump [32, 63–65]; single-leg squat [66–69]; and plant and cut [70–73] (Fig. 14.42). Other tests to consider before the patient is released to unrestricted athletic activities include the multistage fitness test to estimate VO_2max [74] and the 60-second sit-up test or other core strength measures [75].

A trial of function is encouraged in which the patient is monitored for knee swelling, pain, overuse symptoms, and giving-way episodes. Some athletes will experience transient knee swelling upon return to strenuous activities and should be educated on how to recognize this problem and the importance of reducing activities until the swelling subsides. If swelling persists, the athlete is advised to reduce athletics for 2–6 weeks, consider use of nonsteroidal anti-inflammatories, and use ice and elevation. Upon successful return to activity, the patient is encouraged to continue

Table 14.7 Criteria for release to unrestricted sports activities

Test	Criteria for release to sports
Range of knee motion	IKDC normal or nearly normal
Lachman	IKDC normal or nearly normal
Pivot shift	IKDC normal or nearly normal
Patellar pain	None
Knee joint effusion	None
KT-2000 (134 N total anteroposterior displacement)	≤3 mm reconstructed—normal contralateral knee
Isokinetic muscle (180°/s and 300°/s)	<10% deficit quadriceps and hamstrings compared with contralateral side
Isometric muscle (use if isokinetic equipment not available: portable fixed or handheld dynamometer, quadriceps 60° flexion, hamstrings 60° or 90° flexion, three reps each, use mean)	<10% deficit quadriceps and hamstrings compared with the contralateral side
One-repetition maximum leg press (use if isokinetic and isometric equipment not available)	<10% deficit quadriceps and hamstrings compared with the contralateral side
Single-leg hops: any two (single hop, triple hop, triple crossover hop, timed hop) [59]	≤15% deficit lower limb symmetry on any two tests
Video drop-jump [32]	If software available: >60% normalized knee separation distance If software not available, subjective analysis landing position, no valgus, knees flexed for controlled landing
Video single-leg squat (5 reps) [77]	Subjective analysis: no knee valgus, medial-lateral movement, or pelvic tilt
Video plant and cut (patient runs 5 m to a spot designated on the floor with tape, plants on the reconstructed leg, and then performs a 45° cut) [73]	Subjective analysis: high hip and knee flexion, upright posture, no valgus collapse

IKDC International Knee Documentation Committee

Fig. 14.42 Final assessment for return to sports includes (**a**) instrumented Lachman test, (**b**) isokinetic test, (**c**) single-leg hop test, (**d**) single-leg squat test, and (**e**) video drop-jump test (from Noyes and Barber-Westin [76])

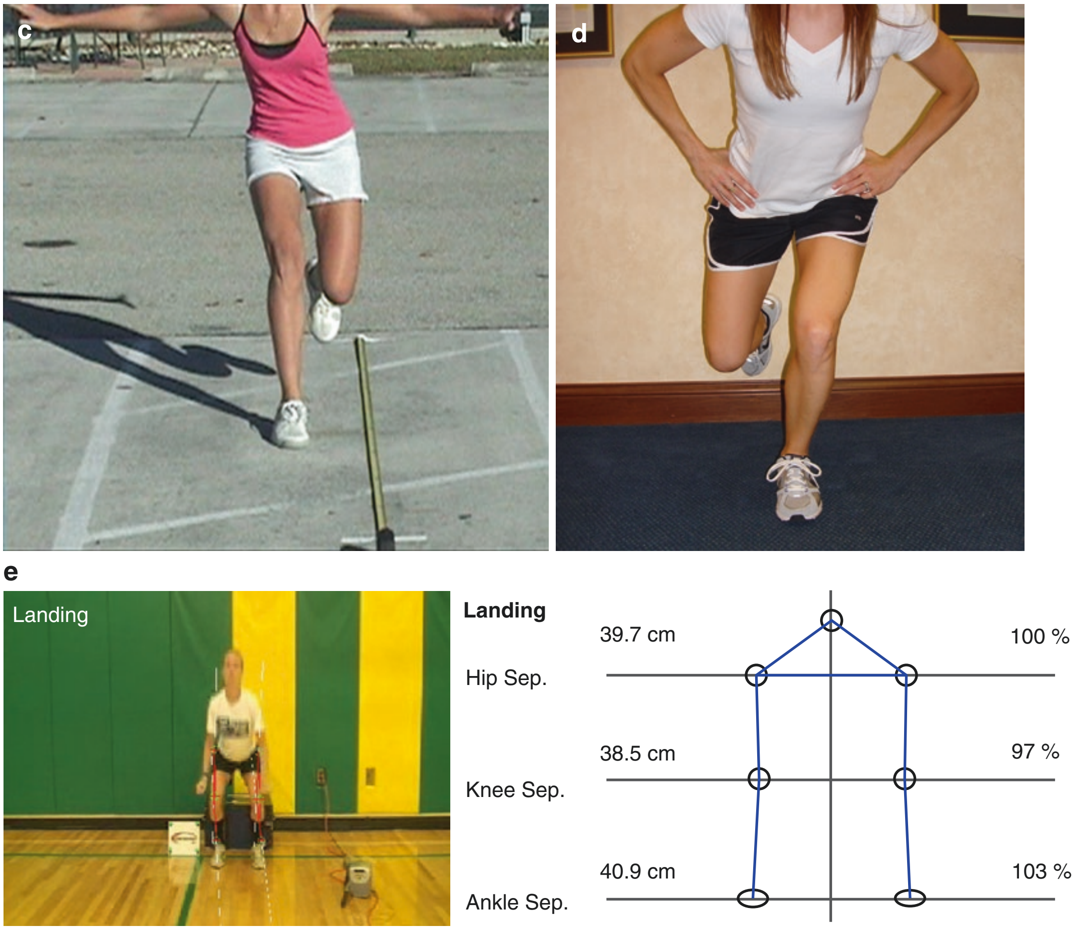


Fig. 14.42 (continued)

with a maintenance program. During the in-season, a conditioning program of two workouts a week is recommended. In the off-season or pre-season, this program should be performed three times a week to maximize gains in flexibility, strength, and cardiovascular endurance.

Critical Points

- Criteria for return to unrestricted sports:
  - Successful completion of Sportsmetrics training
  - Normal knee stability, range of knee motion
  - No swelling, pain, instability with any activity
  - ≤10% deficit isokinetic peak torque quadriceps, hamstrings
  - ≤10% deficit in distance hopped on single-leg hop tests
  - ≥60% normalized knee separation distance video drop-jump test
  - No knee valgus, medial–lateral movement, pelvic tilt on single-leg squat
  - High hip and knee flexion, upright posture, no valgus collapse on the plant and cut drill

References

1. Faltstrom A, Hagglund M, Magnusson H, Forssblad M, Kvist J. Predictors for additional anterior cruciate ligament reconstruction: data from the Swedish national ACL register. Knee Surg Sports Traumatol Arthrosc. 2016;24:885. https://doi.org/10.1007/s00167-014-3406-6.
2. Hettrich CM, Dunn WR, Reinke EK, MOON Group, Spindler KP. The rate of subsequent surgery and predictors after anterior cruciate ligament reconstruction: two- and 6-year follow-up results from a multicenter cohort. Am J Sports Med. 2013;41(7):1534–40. https://doi.org/10.1177/0363546513490277.
3. Hui C, Salmon LJ, Kok A, Maeno S, Linklater J, Pinczewski LA. Fifteen-year outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft for "isolated" anterior cruciate ligament tear. Am J Sports Med. 2011;39(1):89–98. https://doi.org/10.1177/0363546510379975.
4. Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, Consortium M, Spindler KP. Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: prospective analysis of 2488 primary ACL reconstructions from the MOON cohort. Am J Sports Med. 2015;43(7):1583–90. https://doi.org/10.1177/0363546515578836.
5. Kamien PM, Hydrick JM, Replogle WH, Go LT, Barrett GR. Age, graft size, and Tegner activity level as predictors of failure in anterior cruciate ligament reconstruction with hamstring autograft. Am J Sports Med. 2013;41(8):1808–12. https://doi.org/10.1177/0363546513493896.
6. Magnussen RA, Lawrence JT, West RL, Toth AP, Taylor DC, Garrett WE. Graft size and patient age are predictors of early revision after anterior cruciate ligament reconstruction with hamstring autograft. Arthroscopy. 2012;28(4):526–31. https://doi.org/10.1016/j.arthro.2011.11.024.
7. Maletis GB, Inacio MC, Funahashi TT. Risk factors associated with revision and contralateral anterior cruciate ligament reconstructions in the Kaiser Permanente ACLR registry. Am J Sports Med. 2015;43(3):641–7. https://doi.org/10.1177/0363546514561745.
8. Morgan MD, Salmon LJ, Waller A, Roe JP, Pinczewski LA. Fifteen-year survival of endoscopic anterior cruciate ligament reconstruction in patients aged 18 years and younger. Am J Sports Med. 2016;44(2):384–92. https://doi.org/10.1177/0363546515623032.
9. Park SY, Oh H, Park S, Lee JH, Lee SH, Yoon KH. Factors predicting hamstring tendon autograft diameters and resulting failure rates after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2013;21(5):1111–8. https://doi.org/10.1007/s00167-012-2085-4.
10. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. Am J Sports Med. 2014;42(7):1567–73. https://doi.org/10.1177/0363546514530088.
11. Persson A, Fjeldsgaard K, Gjertsen JE, Kjellsen AB, Engebretsen L, Hole RM, Fevang JM. Increased risk of revision with hamstring tendon grafts compared with patellar tendon grafts after anterior cruciate ligament reconstruction: a study of 12,643 patients from the Norwegian Cruciate Ligament Registry, 2004-2012. Am J Sports Med. 2014;42(2):285–91. https://doi.org/10.1177/0363546513511419.
12. Ponce BA, Cain EL Jr, Pflugner R, Fleisig GS, Young BL, Boohaker HA, Swain TA, Andrews JR, Dugas JR. Risk factors for revision anterior cruciate ligament reconstruction. J Knee Surg. 2016;29(4):329–36. https://doi.org/10.1055/s-0035-1554925.
13. Salmon LJ, Russell VJ, Refshauge K, Kader D, Connolly C, Linklater J, Pinczewski LA. Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. Am J Sports Med. 2006;34(5):721–32.
14. Schlumberger M, Schuster P, Schulz M, Immendorfer M, Mayer P, Bartholoma J, Richter J. Traumatic graft rupture after primary and revision anterior cruciate ligament reconstruction: retrospective analysis of incidence and risk factors in 2915 cases. Knee Surg Sports Traumatol Arthrosc. 2017;25:1535. https://doi.org/10.1007/s00167-015-3699-0.
15. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med. 2009;37(2):246–51.
16. Thompson S, Salmon L, Waller A, Linklater J, Roe J, Pinczewski L. Twenty-year outcomes of a longitudinal prospective evaluation of isolated endoscopic anterior cruciate ligament reconstruction with patellar tendon autografts. Am J Sports Med. 2015;43(9):2164–74. https://doi.org/10.1177/0363546515591263.
17. Webster KE, Feller JA. Exploring the high reinjury rate in younger patients undergoing anterior cruciate ligament reconstruction. Am J Sports Med. 2016;44(11):2827–32. https://doi.org/10.1177/0363546516651845.
18. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Am J Sports Med. 2016;44(7):1861–76. https://doi.org/10.1177/0363546515621554.
19. Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. Arthroscopy. 2011;27(12):1697–705. https://doi.org/10.1016/j.arthro.2011.09.009.
20. Barber-Westin SD, Noyes FR. 10 - Scientific basis of rehabilitation after anterior cruciate ligament autogenous reconstruction. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed.

Philadelphia: Elsevier; 2017. p. 268–92. https://doi.org/10.1016/B978-0-323-32903-3.00010-X.
21. Heckmann TP, Noyes FR, Barber-Westin SD. 11 - Rehabilitation of primary and revision anterior cruciate ligament reconstruction. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 293–329. https://doi.org/10.1016/B978-0-323-32903-3.00011-1.
22. Barber-Westin SD, Noyes FR, Heckmann TP, Shaffer BL. The effect of exercise and rehabilitation on anterior-posterior knee displacements after anterior cruciate ligament autograft reconstruction. Am J Sports Med. 1999;27(1):84–93.
23. Barber-Westin SD, Noyes FR. The effect of rehabilitation and return to activity on anterior-posterior knee displacements after anterior cruciate ligament reconstruction. Am J Sports Med. 1993;21(2):264–70.
24. Noyes FR, Mangine RE, Barber S. Early knee motion after open and arthroscopic anterior cruciate ligament reconstruction. Am J Sports Med. 1987;15(2):149–60.
25. Noyes FR, Berrios-Torres S, Barber-Westin SD, Heckmann TP. Prevention of permanent arthrofibrosis after anterior cruciate ligament reconstruction alone or combined with associated procedures: a prospective study in 443 knees. Knee Surg Sports Traumatol Arthrosc. 2000;8(4):196–206.
26. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med. 1996;24(6):765–73.
27. Barber-Westin SD, Hermeto AA, Noyes FR. A six-week neuromuscular training program for competitive junior tennis players. J Strength Cond Res. 2010;24(9):2372–82. https://doi.org/10.1519/JSC.0b013e3181e8a47f.
28. Noyes FR, Barber-Westin SD, Smith ST, Campbell T. A training program to improve neuromuscular indices in female high school volleyball players. J Strength Cond Res. 2011;25(8):2151–60. https://doi.org/10.1519/JSC.0b013e3181f906ef.
29. Noyes FR, Barber-Westin SD, Smith ST, Campbell T, Garrison TT. A training program to improve neuromuscular and performance indices in female high school basketball players. J Strength Cond Res. 2012;26(3):709–19. https://doi.org/10.1519/JSC.0b013e318228194c.
30. Noyes FR, Barber-Westin SD, Tutalo Smith ST, Campbell T. A training program to improve neuromuscular and performance indices in female high school soccer players. J Strength Cond Res. 2013;27(2):340–51. https://doi.org/10.1519/JSC.0b013e31825423d9.
31. Noyes FR, Barber-Westin SD. Neuromuscular retraining in female adolescent athletes: effect on athletic performance indices and noncontact anterior cruciate ligament injury rates. Sports. 2015;3:56–76. https://doi.org/10.3390/sports3020056.
32. Noyes FR, Barber-Westin SD, Fleckenstein C, Walsh C, West J. The drop-jump screening test: difference in lower limb control by gender and effect of neuromuscular training in female athletes. Am J Sports Med. 2005;33(2):197–207.
33. Wilkerson GB, Colston MA, Short NI, Neal KL, Hoewischer PE, Pixley JJ. Neuromuscular changes in female collegiate athletes resulting from a plyometric jump-training program. J Athl Train. 2004;39(1):17–23.
34. Chelly MS, Hermassi S, Shephard RJ. Effects of in-season short-term plyometric training program on sprint and jump performance of young male track athletes. J Strength Cond Res. 2015;29(8):2128–36. https://doi.org/10.1519/JSC.0000000000000860.
35. Chelly MS, Hermassi S, Aouadi R, Shephard RJ. Effects of 8-week in-season plyometric training on upper and lower limb performance of elite adolescent handball players. J Strength Cond Res. 2014;28(5):1401–10. https://doi.org/10.1519/JSC.0000000000000279.
36. Ramirez-Campillo R, Meylan C, Alvarez C, Henriquez-Olguin C, Martinez C, Canas-Jamett R, Andrade DC, Izquierdo M. Effects of in-season low-volume high-intensity plyometric training on explosive actions and endurance of young soccer players. J Strength Cond Res. 2014;28(5):1335–42. https://doi.org/10.1519/JSC.0000000000000284.
37. Ramirez-Campillo R, Alvarez C, Henriquez-Olguin C, Baez EB, Martinez C, Andrade DC, Izquierdo M. Effects of plyometric training on endurance and explosive strength performance in competitive middle- and long-distance runners. J Strength Cond Res. 2014;28(1):97–104. https://doi.org/10.1519/JSC.0b013e3182a1f44c.
38. Vaczi M, Tollar J, Meszler B, Juhasz I, Karsai I. Short-term high intensity plyometric training program improves strength, power and agility in male soccer players. J Hum Kinet. 2013;36:17–26. https://doi.org/10.2478/hukin-2013-0002.
39. Barber-Westin SD, Noyes FR. Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. Phys Sportsmed. 2011;39(3):100–10. https://doi.org/10.3810/psm.2011.09.1926.
40. Wroble RR, Van Ginkel LA, Grood ES, Noyes FR, Shaffer BL. Repeatability of the KT-1000 arthrometer in a normal population. Am J Sports Med. 1990;18(4):396–9.
41. Daniel DM, Malcom LL, Losse G, Stone ML, Sachs R, Burks R. Instrumented measurement of anterior laxity of the knee. J Bone Joint Surg Am. 1985;67(5):720–6.
42. Zaffagnini S, Bruni D, Marcheggiani Muccioli GM, Bonanzinga T, Lopomo N, Bignozzi S, Marcacci M. Single-bundle patellar tendon versus non-anatomical double-bundle hamstrings ACL reconstruction: a prospective randomized study at 8-year minimum follow-up. Knee Surg Sports Traumatol Arthrosc. 2011;19(3):390–7. https://doi.org/10.1007/s00167-010-1225-y.
43. Choi NH, Lee JH, Son KM, Victoroff BN. Tibial tunnel widening after anterior cruciate ligament reconstructions with hamstring tendons using Rigidfix femoral fixation and Intrafix tibial fixation. Knee Surg Sports Traumatol Arthrosc. 2010;18(1):92–7. https://doi.org/10.1007/s00167-009-0951-5.

44. Landes S, Nyland J, Elmlinger B, Tillett E, Caborn D. Knee flexor strength after ACL reconstruction: comparison between hamstring autograft, tibialis anterior allograft, and non-injured controls. Knee Surg Sports Traumatol Arthrosc. 2010;18(3):317–24. https://doi.org/10.1007/s00167-009-0931-9.
45. Hartigan EH, Axe MJ, Snyder-Mackler L. Time line for noncopers to pass return-to-sports criteria after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2010;40(3):141–54. https://doi.org/10.2519/jospt.2010.3168.
46. Isberg J, Faxen E, Brandsson S, Eriksson BI, Karrholm J, Karlsson J. Early active extension after anterior cruciate ligament reconstruction does not result in increased laxity of the knee. Knee Surg Sports Traumatol Arthrosc. 2006;14(11):1108–15. https://doi.org/10.1007/s00167-006-0138-2.
47. Sajovic M, Vengust V, Komadina R, Tavcar R, Skaza K. A prospective, randomized comparison of semitendinosus and gracilis tendon versus patellar tendon autografts for anterior cruciate ligament reconstruction: five-year follow-up. Am J Sports Med. 2006;34(12):1933–40.
48. Poehling GG, Curl WW, Lee CA, Ginn TA, Rushing JT, Naughton MJ, Holden MB, Martin DF, Smith BP. Analysis of outcomes of anterior cruciate ligament repair with 5-year follow-up: allograft versus autograft. Arthroscopy. 2005;21(7):774–85.
49. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. Sports Med. 2004;34(4):269–80.
50. Beynnon BD, Johnson RJ, Fleming BC, Kannus P, Kaplan M, Samani J, Renstr m P. Anterior cruciate ligament replacement: comparison of bone-patellar tendon-bone grafts with two-strand hamstring grafts: a prospective, randomized study. J Bone Joint Surg Am. 2002;84-A(9):1503.
51. Henriksson M, Rockborn P, Good L. Range of motion training in brace vs. plaster immobilization after anterior cruciate ligament reconstruction: a prospective randomized comparison with a 2-year follow-up. Scand J Med Sci Sports. 2002;12(2):73–80.
52. Moller E, Forssblad M, Hansson L, Wange P, Weidenhielm L. Bracing versus nonbracing in rehabilitation after anterior cruciate ligament reconstruction: a randomized prospective study with 2-year follow-up. Knee Surg Sports Traumatol Arthrosc. 2001;9(2):102–8.
53. Stark T, Walker B, Phillips JK, Fejer R, Beck R. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. PM R. 2011;3(5):472–9. https://doi.org/10.1016/j.pmrj.2010.10.025.
54. Toonstra J, Mattacola CG. Test-retest reliability and validity of isometric knee-flexion and -extension measurement using 3 methods of assessing muscle strength. J Sport Rehabil. 2013;22(1). https://doi.org/10.1123/jsr.2013.TR7.
55. Whiteley R, Jacobsen P, Prior S, Skazalski C, Otten R, Johnson A. Correlation of isokinetic and novel hand-held dynamometry measures of knee flexion and extension strength testing. J Sci Med Sport. 2012;15(5):444–50. https://doi.org/10.1016/j.jsams.2012.01.003.
56. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, Newton RU, Triplett NT, Dziados JE. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. J Appl Physiol. 1995;78(3):976–89.
57. Reiman MP, Manske RC. Functional testing in human performance. Champaign: Human Kinetics; 2009.
58. Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. Clin Orthop Relat Res. 1990;(255):204–214.
59. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med. 1991;19(5):513–8.
60. Barrett GR, Luber K, Replogle WH, Manley JL. Allograft anterior cruciate ligament reconstruction in the young, active patient: tegner activity level and failure rate. Arthroscopy. 2010;26(12):1593–601. https://doi.org/10.1016/j.arthro.2010.05.014.
61. Logerstedt D, Grindem H, Lynch A, Eitzen I, Engebretsen L, Risberg MA, Axe MJ, Snyder-Mackler L. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo ACL cohort study. Am J Sports Med. 2012;40(10):2348–56. https://doi.org/10.1177/0363546512457551.
62. Logerstedt D, Di Stasi S, Grindem H, Lynch A, Eitzen I, Engebretsen L, Risberg MA, Axe MJ, Snyder-Mackler L. Self-reported knee function can identify athletes who fail return-to-activity criteria up to 1 year after anterior cruciate ligament reconstruction: a Delaware-Oslo ACL cohort study. J Orthop Sports Phys Ther. 2014;44(12):914–23. https://doi.org/10.2519/jospt.2014.4852.
63. Sigward SM, Havens KL, Powers CM. Knee separation distance and lower extremity kinematics during a drop land: implications for clinical screening. J Athl Train. 2011;46(5):471–5.
64. Nilstad A, Andersen TE, Kristianslund E, Bahr R, Myklebust G, Steffen K, Krosshaug T. Physiotherapists can identify female football players with high knee valgus angles during vertical drop jumps using real-time observational screening. J Orthop Sports Phys Ther. 2014;44(5):358–65. https://doi.org/10.2519/jospt.2014.4969.
65. Pollard CD, Sigward SM, Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. Clin Biomech (Bristol, Avon). 2010;25(2):142–6. https://doi.org/10.1016/j.clinbiomech.2009.10.005.
66. Ireland ML, Durbin T, Bolgla LA. Gender differences in core strength and lower extremity function during the single-leg squat test. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete:

causes, impacts, and conditioning programs. Berlin: Springer-Verlag; 2012. p. 203–19.
67. Ageberg E, Bennell KL, Hunt MA, Simic M, Roos EM, Creaby MW. Validity and inter-rater reliability of medio-lateral knee motion observed during a single-limb mini squat. BMC Musculoskelet Disord. 2010;11:265. https://doi.org/10.1186/1471-2474-11-265.
68. Claiborne TL, Armstrong CW, Gandhi V, Pincivero DM. Relationship between hip and knee strength and knee valgus during a single leg squat. J Appl Biomech. 2006;22(1):41–50.
69. Ireland ML. The female ACL: why is it more prone to injury? Orthop Clin North Am. 2002;33(4): 637–51.
70. Cortes N, Onate J, Van Lunen B. Pivot task increases knee frontal plane loading compared with sidestep and drop-jump. J Sports Sci. 2011;29(1):83–92. https://doi.org/10.1080/02640414.2010.523087.
71. Jones PA, Herrington LC, Munro AG, Graham-Smith P. Is there a relationship between landing, cutting, and pivoting tasks in terms of the characteristics of dynamic valgus? Am J Sports Med. 2014;42(9):2095–102. https://doi.org/10.1177/0363546514539446.
72. Nagano Y, Ida H, Akai M, Fukubayashi T. Biomechanical characteristics of the knee joint in female athletes during tasks associated with anterior cruciate ligament injury. Knee. 2009;16(2):153–8. https://doi.org/10.1016/j.knee.2008.10.012.
73. Pollard CD, Sigward SM, Powers CM. Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. Clin J Sport Med. 2007;17(1):38–42. https://doi.org/10.1097/JSM.0b013e3180305de8.
74. Ramsbottom R, Brewer J, Williams C. A progressive shuttle run test to estimate maximal oxygen uptake. Br J Sports Med. 1988;22(4):141–4.
75. Okada T, Huxel KC, Nesser TW. Relationship between core stability, functional movement, and performance. J Strength Cond Res. 2011;25(1):252–61. https://doi.org/10.1519/JSC.0b013e3181b22b3e.
76. Noyes FR, Barber-Westin SD. Sportsmetrics ACL intervention training program: components and results. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete: causes, impacts, and conditioning programs. 2nd ed. Berlin: Springer-Verlag; 2018. p. 337–76. https://doi.org/10.1007/978-3-662-56558-2_17.
77. Ireland ML, Bolgla LA, Noehren B. Gender differences in core strength and lower extremity function during static and dynamic single-leg squat tests. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete. causes, impacts, and conditioning programs. 2nd ed. Berlin: Springer-Verlag; 2018.

Key Vital Steps in Returning Athletes to Sports Following ACL Surgery

15

Kevin E. Wilk and Christopher A. Arrigo

15.1 Introduction

Return to sport (RTS) participation, at any level, following anterior cruciate ligament (ACL) surgery can be challenging. It is the final step in a 6–12 month process that significantly impacts the individual both during the short-term rehabilitation process as well as for the rest of their life. It can be a difficult and often frustrating undertaking for the patient and clinician, and all too often patients do not reach their preinjury level of activity or sport participation [1–7]. Buller et al. [8] reported that approximately 200,000 ACL injuries are sustained in the United States annually. Wilk et al. [7] noted, based on insurance claim data, that 135,000–145,000 ACL surgeries are performed annually in the United States. In combination, these data reveal that there are both large numbers of individuals who undergo ACL surgery every year and a considerable amount of individuals who chose to exist without an ACL.

Ardern et al. [1] reported that only 63% of ACL reconstructed patients RTS participation at preinjury levels. Other authors have reported the return to preinjury levels of sport range from 60% to 83%, even in professional athletes [2–6]. Statistics reveal that only 78% of National Basketball Association players return to competition following ACL surgery, and of those, 44% exhibit a decrease in performance and player efficiency [4]. In professional football, it has been shown that careers are shortened by about 2 years and performance decreased by 33% following ACL surgery [3, 5, 6].

Although generally present more often in lower-level athletes, kinesiophobia, the fear of movement or reinjury, is the most common reason cited for not being able to return to a preinjury level of participation [2, 9]. Problems with the structures of the knee is the second most reported reason for failure to return to preinjury sports participation or activity [2]. Using the data above, if 140,000 ACL surgeries are performed annually, and only 65% return to preinjury level, there remain nearly 50,000 people who have undergone ACL surgery who are not returning to preinjury or are not confident regarding their knee status. We as clinicians need to do a better job! This is especially true in the later phases of the rehabilitation process when most insurance have restricted or limited physical therapy visits. Basically, patients need this advanced phase to ensure successful outcomes following ACL surgery, but insurance often runs out prematurely. In this chapter, we will discuss the key aspects of the advanced rehabilitation phase we believe are essential in returning a patient to sport participation following ACL injury and/or surgery.

K. E. Wilk (✉)
Sports Medicine, Champion Sports Medicine, Birmingham, AL, USA

C. A. Arrigo
Advanced Rehabilitation, Tampa, FL, USA

MedStar Sports Medicine, Lafayette Centre, Washington, DC, USA
e-mail: carrigo@advancedrehab.us

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_15

15.2 Return to Sport: 10 Critical Steps for Success

Using a criteria-based, scientific evidence-supported approach to rehabilitation after ACL surgery is crucial to systematically and successfully progress an athlete through the rehabilitation process and maximize their odds of an uncomplicated and complete recovery. A stable, functionally asymptomatic knee is the ultimate goal of this process, culminating in the successful return to the athlete's prior level of athletic participation. Getting to this final point of the rehabilitation process requires completing numerous critical steps. We have outlined these 10 vital steps in Table 15.1. These steps span the entire rehabilitation process and represent the building blocks that combine to allow an unfettered RTS participation following ACL surgery. The failure to attain any one of these steps will almost certainly result in the inability of an athlete to return to unrestricted athletic participation.

The current trends seen in ACL rehabilitation can be traced to several articles by Noyes et al. [10] who reported it was safe to use immediate knee motion following ACL reconstruction and to begin early safe functional exercises. Later, Shelbourne and Nitz [11] reported improved clinical outcomes in patients who followed an accelerated rehabilitation program, with their patients exhibiting better strength and range of motion (ROM) with fewer postoperative complications and an earlier RTS. The severity of ACL injuries and the difficulty encountered in returning athletes to unrestricted, high-level activity highlight the need for a sequential, progressive, and structured approach to rehabilitation following ACL surgery, emphasizing full passive knee extension [11–15], immediate motion [4, 10, 14–19], immediate partial weight-bearing (WB) [14, 15, 20, 21], functional exercises [14, 22, 23], and neuromuscular control exercises and drills. Additionally, better motion, improved strength, enhanced function, and improved outcomes have been demonstrated with formal, supervised rehabilitation [24]. We believe that this is a critical element, and when formal rehabilitation is abbreviated and not continued into the advanced portion of the rehabilitation process, the likelihood of a successful return to high-level asymptomatic sport drastically decreases. The rehabilitation program we use including the phases, goals, and the criteria for progression after ACL surgery is presented in Table 15.2.

Table 15.1 Ten keys to return to sport

1. Restore *full* passive knee motion and patellar mobility
2. Normalize quadriceps muscular strength
3. Restore neuromuscular control
4. Retraining change of direction with skill
5. Restore lateral hip strength
6. Stabilize above and below
7. Improve hamstrings strength
8. Teach proper landing technique
9. Teach proper running and cutting technique
10. Allow return to play based on achieving objective criteria

15.2.1 Key Point 1: Restore Full Passive Knee Motion and Patellar Mobility

Immediate motion is essential to avoid ROM complications following ACL surgery [13, 16, 25–27]. The most common complication that contributes to a poor functional outcome following ACL surgery is a loss of motion, particularly a loss of full passive knee extension [13, 28–31]. The inability to fully extend the knee alters joint arthrokinematics [32–35], leads to scar tissue formation in the front of the knee, and increases patellofemoral and tibiofemoral joint contact pressure [36]. This can result in the development of early onset osteoarthritis. It is crucial to achieve some degree of reasonable and safe hyperextension during the first few days after surgery and eventually to work to restore the symmetrical motion.

The interventions to normalize passive knee extension include supine hamstring stretches with a wedge under the heel combined with gastrocnemius stretches with a towel. A passive overpressure of 5–10 lb (2.25–4.5 kg) is applied onto the distal femur just proximal to the patella to establish a low-load, long-duration stretch as needed (Fig. 15.1a). The athlete is instructed to lie supine

Table 15.2 Rehabilitation phases, program goals, and criteria for progression following ACL reconstruction

Phase	Goals	Criteria to progress to next phase
Preoperative	Diminish inflammation, swelling, and pain Restore normal range of motion (especially knee extension) Restore voluntary muscle activation Provide patient education to prepare for surgery	NA
Immediate postoperative (day 1–7)	Restore full passive knee extension Diminish joint swelling and pain Restore patellar mobility Gradually improve knee flexion Re-establish quadriceps control Restore independent ambulation	Quadriceps control (ability to perform good quad set and straight leg raises) Full passive knee extension Passive ROM: 0–90° Good patellar mobility Minimal joint effusion Independent ambulation
Early rehabilitation (week 2–4)	Maintain full passive knee extension (at least 0 to 5–7 hyperextension) Gradually increase knee flexion Diminish remaining swelling and pain Improve muscle control and activation Restore proprioception/neuromuscular control Normalize patellar mobility	Active range of motion 0–115° Quadriceps strength 60% > contralateral side (isometric test at 60° of knee flexion) Unchanged KT test bilateral values (=1 or less) Minimal to no knee joint effusion No joint line or patellofemoral pain
Progressive strengthening and neuromuscular control (week 4–10)	Restore full knee range of motion (0–125°) Improve lower extremity strength Enhance proprioception, balance, and neuromuscular control Improve muscular endurance Restore limb confidence and function	Active ROM 0–125° or greater Quadriceps strength 75% of contralateral side Knee extension flexor:extensor ration 70–75% No change in KT values (comparable with contralateral side, within 2 mm) No pain or effusion Satisfactory clinical examination Satisfactory isokinetic test (values at 180°/s): 1. Quadriceps bilateral comparison 75% 2. Hamstring strength equal bilaterally 3. Quadriceps peak torque/body weight ratios: 65% males, 55% females Single-leg hop test 80% of contralateral leg Subjective knee scoring (modified Noyes system): ≥80 points
Advanced activity (week 10–16)	Normalize lower extremity strength Enhance muscular poser and endurance Improve neuromuscular control Perform selected sport-specific drills	Full range of motion Unchanged KT test (<2.5 mm of opposite side) Isokinetic test that fulfills criteria 1. Quadriceps bilateral comparison ≥80% 2. Hamstring bilateral comparison ≥110% 3. Quadriceps torque/body weight ratio ≥55% 4. Hamstring/quadriceps ratio ≥70% Proprioceptive test 100% of contralateral leg Functional test ≥85% of contralateral side Satisfactory clinical examination Subjective knee scoring (modified Noyes system) ≥90 points
Return to activity (week 16–22)	Gradual return to full unrestricted sports Achieve maximal strength and endurance Normalize neuromuscular control Progress skill training	

KT knee arthrometer, *NA* not applicable, *ROM* range of motion

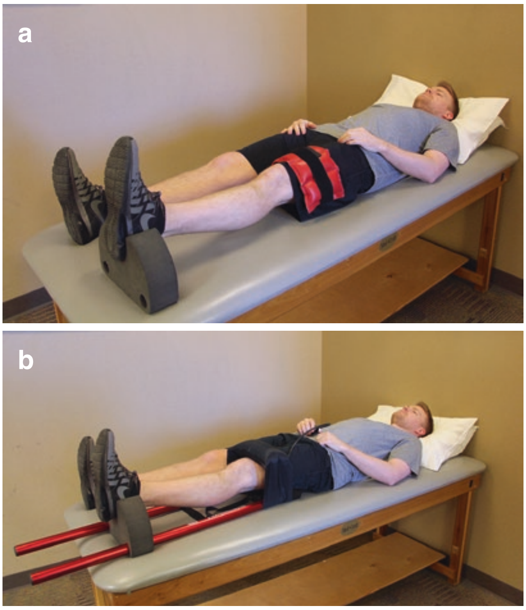


Fig. 15.1 (**a**) A low-load, long-duration stretch to restore the patient's full passive knee extension. A 4.5-kg weight is used for 10–15 min, with a bolster placed under the ankle to create a stretch. (**b**) Commercial device (Extensionater; ERMI, Inc, Atlanta, GA) to improve extension range of motion and prevent compensatory hip external rotation

while the low-load, long-duration stretch is applied for 12–15 min, four times per day, with the total low-load, long-duration stretch applied for at least 60 min daily [37]. We use this technique immediately following surgery, not only to maintain and improve knee extension, but to prevent the formation of a flexion contracture or a cyclops lesion.

Hyperextension is restored based on the amount exhibited by the uninvolved knee. When an athlete exhibits 10° or more of hyperextension on the uninjured knee, we will strive to restore approximately 7° of hyperextension on the surgical side during the first week post surgery and then gradually restore the remaining hyperextension once joint inflammation is reduced and muscular control of the quadriceps is restored. We often use extension devices to create an overpressure into extension (Fig. 15.1b). Restoring full passive knee extension or some appropriate degree of hyperextension compared with the uninjured limb is imperative for a successful outcome and long-term asymptomatic knee [38].

Unlike extension, knee flexion should be gradually restored during the rehabilitation process. If flexion is pushed too aggressively initially, swelling will result and limit progress. The overall goal must be the restoration of full knee flexion, eventually pushing the heel to the gluteals passively in a prone position. The gradual progression of knee flexion milestones includes 0° to 90° in the first 5–7 days after surgery, 0–100°, 7–10 days after surgery, and a 10° increase in passive knee flexion weekly until full passive flexion is attained (typically between 4 and 6 weeks following surgery) [39]. If a substantial effusion exists, ROM is advanced at a slower pace. Our preference is not to be aggressive with knee flexion the first 5–7 days after surgery, focusing on reducing pain and swelling rather than aggressively pushing knee flexion and increasing symptoms.

Complete patellar mobility helps prevent anterior knee pain following ACL surgery. Not only does patellar mobility enable the restoration of full knee motion, it is also required for normal quadriceps function and protects the patella from excessive wear and tear. The loss of patellar mobility following ACL reconstruction may have various causes, including excessive scar tissue adhesions along the medial and lateral retinacula, fat pad restrictions [36, 40], and harvesting the ipsilateral patellar tendon ACL graft. A loss of superior patellar mobility and an infrapatella contracture syndrome results in ROM complications, poor quadriceps activation, and ambulation with a flexed knee gait [41]. Patellar mobilizations should be performed by the rehabilitation specialist clinically and independently by patients during their home exercise program. Mobilizations are performed in the medial/lateral and superior/inferior directions. This is a clinical imperative for those with a patellar tendon autograft to restore the patella's ability to tilt and glide, especially in the superior direction.

15.2.2 Key Point 2: Normalize Quadriceps Strength

Asymmetry in quadriceps strength after ACL surgery alters knee joint kinematics and adversely affects the athlete's ability to RTS [42]. Several outcome studies have documented that symmetrical quadriceps are essential to a successful injury-free RTS [43, 44]. Inhibition of the quadriceps muscle is common after ACL surgery, especially in the presence of pain and effusion during the acute phases of rehabilitation. Regaining volitional quadriceps function and restoring full bilateral strength are critical to the pain-free, fully functioning knee. Electrical muscle stimulation and biofeedback [45] are often incorporated during therapeutic exercises to facilitate the active contraction of the quadriceps musculature. Based on a review of the literature, Kim et al. [46] concluded that using neuromuscular electrical stimulation combined with exercise was more efficient than exercise alone to improve the quadriceps strength after ACL surgery.

Clinically, we advocate the use of electrical stimulation immediately following surgery while performing isometric and isotonic exercises including quadriceps setting, straight leg raises, hip adduction and abduction, and knee extensions from 90° to 40° of knee flexion [47]. Patients are instructed to actively contract the quadriceps musculature with the assistance of the superimposed neuromuscular electrical stimulation. The patient must concentrate on independently activating the quadriceps during rehabilitation. Once independent muscle activation is achieved, biofeedback may be used to facilitate further neuromuscular activation of the quadriceps. The authors prefer electrical muscle stimulation to biofeedback for the vast majority of patients. Furthermore, to assist in retarding quadriceps muscular atrophy and facilitate hypertrophy in the intermediate to advanced phases of rehabilitation, we use blood flow restriction (BFR) to the lower extremity during exercise. Empirically, we have been very pleased with the results seen using BFR during the rehabilitation process.

15.2.3 Key Point 3: Restoration of Neuromuscular Control and Dynamic Functional Stability

Proprioception and perturbation activities initiated early in the postoperative program serve to not only restore the neuromuscular control of the lower quarter, but also to improve RTS. Basic proprioceptive training begins during the second postoperative week once pain and swelling improve and quadriceps control is regained [48–51]. Proprioceptive training initially begins with basic exercises such as joint repositioning and weight-shifting. Weight shifts may be performed in the medial/lateral direction and in diagonal patterns. Mini-squats are also initiated soon after surgery.

By approximately the end of week 2, mini-squats are progressed to be performed on an unstable surface, such as foam or a tilt board, if the patient exhibits good postural control and form during a double-leg squat on a solid surface. The patient is instructed to squat to approximately 30–45° and to hold the position for 2–3 s while stabilizing the tilt board. Wilk et al. [47] showed that the greatest amount of hamstring and quadriceps co-contraction occurred at approximately 30° of knee flexion during the squat. Squats may be performed with the tilt board positioned to move in the medial/lateral or anterior/posterior direction. Based on previous studies showing that muscular contraction can decrease knee varus/valgus laxity [52] and that quadriceps-to-hamstring muscle strength imbalances lead to an increased risk of ligamentous injury [2], we believe that improving neuromuscular coactivation enhances knee stability. As proprioception improves, drills to encourage preparatory agonist/antagonist coactivation during functional activities are also incorporated at this point in the process. These dynamic stabilization drills begin during the first 3 weeks following surgery with a single-leg stance on flat ground and unstable surfaces, cone stepping, and lateral lunge drills.

Single-leg balance exercises, performed on a piece of foam with the knee slightly flexed, are progressed by incorporating random movement of either the upper extremity or the uninvolved lower extremity to alter the position of the center of mass. Eventually, both upper and lower extremity movements may be combined in these exercises. (Fig. 15.2) These single-leg balance drills with extremity movement are used to promote dynamic stabilization, improve single-leg

Fig. 15.2 Single-leg balance on an unstable surface with superimposed upper extremity movement

stability, and recruit the activation of a number of lower extremity muscle groups [53]. Medicine balls of progressively heavier weight can also be incorporated to provide a further challenge to the neuromuscular control system during this type of exercise activity.

Perturbation training is also initiated at approximately 3 weeks following surgery. Fitzgerald et al. [54] examined the efficacy of perturbation training in a rehabilitation program for ACL-deficient knees and reported more satisfactory outcomes and a lower frequency of subsequent giving-way episodes when perturbation training is incorporated in the rehabilitation program. Wilk et al. [21], studying female patients after ACL surgery, observed improved results when a program emphasized perturbation training. Therefore, we incorporate perturbation training while the patient performs double- or single-leg balance exercises on a tilt board or an unstable surface. While flexing the knee to approximately 30°, the patient stabilizes the tilt board and begins throwing and catching a 3–5 lb (1.4–2.3 kg) medicine ball. The patient is instructed to stabilize the tilt board in reaction to the sudden outside force produced by the weighted ball. The rehabilitation specialist may also provide perturbations by striking the tilt board with the foot, requiring the patient to stabilize the tilt board with dynamic muscular contractions (Fig. 15.3). Perturbations may also be performed during this drill by tapping the patient on the hips and trunk to provide a postural disturbance to the body. We typically utilize three levels of the tilt board to advance the patient into progressively more challenging degrees of instability.

Fig. 15.3 Single-leg stance (knee flexed at 30°) performed on a tilt board while throwing and catching a 3.2-kg plyoball. Manual perturbations are performed by tapping the tilt board with the clinician's foot to create a postural disturbance

Additionally, when neuromuscular training is initiated early in the rehabilitation program and continually advanced throughout the process, the athlete's confidence in the injured knee improves. It has been our experience that, following a serious knee injury, athletes may become afraid of reinjury and returning to high-level function and restoring neuromuscular control in the form of advancing their perturbation skill significantly improves confidence in the injured knee [55]. Finally, proprioceptive and neuromuscular control has been shown to diminish once muscular fatigue occurs [56–58]. Therefore, performing neuromuscular control drills and exercises toward the end of a treatment session, after cardiovascular training, serves to further challenge neuromuscular control of the knee joint when the dynamic stabilizers are fatigued enhancing the clinical effectiveness of these activities.

15.2.4 Key Point 4: Retrain the Ability to Change Direction with Skill

Often, agility drills such as running through ladders, or other agility drills, are performed in one direction from start to finish. We believe the athlete should be trained to perform the change of direction drills based on the physical therapists' verbal commands to retrain the ability to athletically change direction during activity. For example, the patient would perform a forward chopping motion running through the ladder, and on verbal instructions, we say "switch" and they perform a lateral chopping motion. We can also say "reverse" to reverse the athlete's direction. This drill is all based on the athlete's ability to react and to change directions (Fig. 15.4).

Fig. 15.4 Ladder drill with change of direction

15.2.5 Key Point 5: Restore Lateral Hip Strength

Lateral hip strength is critical to successful rehabilitation and RTS after ACL reconstruction. Restoration of the athlete's lateral hip strength helps prevent the femur from adducing and internally rotating, thus causing valgus collapse of the knee. We believe lateral hip strength is critical for athletes to achieve and that it helps to restore pain-free function and prevent additional lower extremity injuries. Improved lateral hip strength following ACL surgery is attained through the use of movements that facilitate a change in planes of motion during the drill or exercise, such as lateral slides and reactive lateral slides.

Forward, backward, and lateral cone or cup step-over drills are initially used to facilitate gait training, enhance dynamic stability, and train the hip to help control forces at the knee joint. The athlete steps over the obstacle by raising their knee to the level of the hip and stepping over a series of cones, landing with a slightly flexed knee. These cone drills may also be performed at various speeds to train the lower extremity to dynamically stabilize with different amounts of

Fig. 15.5 Lateral lunges performed using a sport cord for resistance while landing on a foam pad and catching a ball. The patient is instructed to land and maintain a knee flexion angle of 30° during the drill

momentum. Strengthening of the hip and knee to eccentrically control the lower extremity is imperative to regain function, and these drills serve to improve knee stability via proximal and distal muscular activation.

Lateral lunges are also performed to improve dynamic stability. The athlete is instructed to lunge to the side, land on a slightly flexed knee, and hold that position for 1–2 s before returning to the start position. We use a functional progression for lateral lunges in which straight plane lateral lunges are performed first, which then progress to multiple plane/diagonal lunges, lateral lunges with rotation, and lateral lunges onto foam (Fig. 15.5). As the athlete progresses, a ball toss can be added to any of these exercises to challenge the preparatory stabilization of the lower extremity with minimal conscious awareness.

The exercises and drills we prefer to activate and recruit lateral hip musculature include single-leg squats, lateral slides, bridging, clams, Russian deadlift (RDL), star drills, and perturbation drills on a rocker board.

15.2.6 Key Point 6: Knee Control Must Be Provided from Both Above and Below

Stabilization of the knee joint occurs from above and below the knee, requiring a focus on restoring the control of the hip complex during the rehabilitation program. Emphasis should be placed on activation and control of the hip abductors and external rotators, as well as strengthening the hip extensors, hamstrings, gastrocnemius–soleus complex, and posterior tibialis musculature. Special consideration is taken to eccentrically train the hip abductors, extensors, and external rotators because these muscle groups help control excessive adduction and internal rotation of the femur during WB activities. Moreover, core stabilization exercises are used to aid in controlling lateral trunk displacement during functional athletic movements [59–63]. We believe that after ACL surgery, it is important that female athletes undergo a specific rehabilitation program that addresses the predisposing factors that potentially led to the injury, focusing on retraining faulty mechanics and improving muscular imbalances.

Static and dynamic control and balance activities need to be incorporated aggressively with the goal of training the hip and lower leg to control dynamic valgus positions. This is accomplished through retraining the lower quarter musculature and improving joint position sense to minimize or eliminate the impact of hip internal rotation and adduction moments, as well as reducing the impact of foot pronation to assist in reducing the valgus collapse of the knee.

Specific exercises and drills we prefer to accomplish this type of control include front step-downs, single-leg squats with TheraBand CLX spiraled around the athlete's leg and waist (Fig. 15.6), double- and single-leg bridging, single-leg stance and balance with resistance bands pulling into knee valgus and the athlete resisting the movement (Fig. 15.7), lateral slides, and the star drill.

15.2.7 Key Point 7: Improve Hamstrings Activation and Strength

We believe that it is important to not only strengthen the hamstring musculature but also to improve hamstring reaction time following ACL surgery. It has been expressed that the hamstrings

Fig. 15.6 Single-leg squat with TheraBand CLX spiraled around legs and waist

Fig. 15.7 Single-leg stance with resistance band opposing valgus pull

help reduce ACL strain during running, cutting, and other functional activities. Therefore, it is important to perform hamstring training in these functional patterns of movement. We believe that to improve hamstring recruitment and reaction

Fig. 15.8 Supine bridge on stability ball with hamstring curl

Fig. 15.9 Nordic hamstring exercise on a Norbord

time, some nontraditional exercises should be performed. These exercises include supine bridging onto a stability ball with hamstring curls (Fig. 15.8), backward running, Nordic hamstrings, Nordic hamstrings on a Norbord (Fig. 15.9), and fast-speed hamstring contractions.

15.2.8 Key Point 8: Teach Proper Landing Technique

Because a common mechanism of noncontact ACL injury is a valgus stress with rotation at the knee, it is important for the athlete to learn to control this type of valgus moment during activity [64–66]. In addition to education on optimal knee alignment (keeping the knee over the second toe), exercises designed to control these valgus moments at the knee include front step-downs (Fig. 15.10), lateral step-downs with resistance (Fig. 15.11), and squats with resistance around the distal femur

Fig. 15.10 Front step-down movement: during the eccentric or lowering phase, the patient is instructed to maintain proper alignment of the lower extremity to prevent the knee from moving into a valgus moment

Fig. 15.11 Lateral step-down with resistance bands. A resistance band is applied around the inner knee to provide resistance and to control the valgus moment at the knee by recruiting hip abductors and rotators

Fig. 15.12 Lateral stepping with resistance bands around the distal femur to further recruit hip musculature

(Fig. 15.12). Rehabilitation should train the athlete to stabilize the knee through coactivation of the quadriceps and hamstrings using various exercises, including tilt board balance exercises while performing a throw and catch.

Dynamic stabilization drills must be performed, with the knee flexed approximately 30° to promote better alignment and activation of the quadriceps and hamstring musculature to facilitate landing in a coactivated position [59, 64]. In this manner, the hip extensors, external rotators, abductors, and core stabilizers are trained while emphasizing a flexed knee posture during running, cutting, and jumping, thereby working to control the knee position via the hip/pelvis [60, 67, 68] and foot position [67]. Both WB and non-WB exercises (NWBE) have been shown to be effective for rehabilitation and RTS after ACL surgery [11]. However, compared to NWBE, individuals who perform WB exercises predominantly tend to have less knee pain, have stable knees, are generally more satisfied with the end result, and achieve an overall quicker RTS [11].

Plyometric jumping drills are also performed to facilitate dynamic stabilization and neuromuscular control of the knee joint and to train for the dissipation of forces across the lower extremity through the muscle's stretch-shortening properties [69, 70]. Hewett et al. [64] examined the effects of a 6-week plyometric training program on the landing mechanics and strength of female athletes and reported a 22% decrease in peak ground reaction forces and a 50% decrease in the abduction/adduction moments at the knee during landing. Moreover, significant increases in hamstring isokinetic strength, the hamstring–quadriceps ratio, and vertical jump height were reported [64]. Using the same plyometric program, Hewett et al. [59] reported a statistically significant decrease in the amount of ACL injuries seen in female athletes. It must be emphasized that with plyometric drills, it is important to instruct the athlete on proper jumping and landing techniques as well as the control and dissipation of forces.

Plyometric activities are typically initiated 12–16 weeks after a patellar tendon autograft reconstruction and delayed until 16–20 weeks following a semitendinosus autograft. The leg press machine is initially used to perform plyometrics horizontally, controlling the amount of weight and ground reaction forces as the athlete learns to correctly perform jumping drills. The athlete is instructed to land softly on the toes, with the knees slightly flexed, to maximize force dissipation and avoid knee hyperextension. Plyometric drills are then progressed to flat ground and include ankle hops, jumping in place, and lateral, diagonal, and rotational jumping, bounding, and skip lunging. Flat ground plyometrics are progressed to incorporate single and multiple boxes (Fig. 15.13). We usually begin plyometric activities with double-leg jumps, progressing to single-leg jumps. We are cautious with plyometric training because of its potential negative effects on articular surfaces, bone bruises, and the menisci. We do not advocate the use of plyometrics for the low-level recreational athlete.

Fig. 15.13 Double-leg plyometric jumping drills in the lateral direction, in which the patient is instructed to land on the box and flat ground with the knee in a flexed position. These activities are initiated to allow the quadriceps musculature to create and dissipate forces at a higher level prior to returning to sport

15.2.9 Key Point 9: Teach Proper Running and Cutting Technique

Proper running form and technique is not only essential for full pain-free knee function, but also to restore high-level knee function. During the rehabilitation process, specific running technique drills can be performed to ensure proper running and cutting techniques are restored. During the early running phase, form running drills are performed (Fig. 15.14), as well as resisted running

Fig. 15.14 Form running drill

(Fig. 15.15) and acceleration/deceleration drills. In addition, running, deceleration, and cutting maneuvers are performed, first at 50% intensity and then gradually increases in intensity as rehabilitation

Fig. 15.15 Resisted running

progresses. Often, we will use video to record the athlete's running and cutting technique in order to analyze performance and provide visual explanation to the athlete regarding proper technique and performance.

15.2.10 Key Point 10: Use Objective Criteria Fulfillment for Progression Back to Sport

"When can I start running?" This is one of the most frequently asked questions of almost any athlete following ACL surgery. The simple answer for any athlete is they can start running when they are ready to run. Giving an athlete a specific time frame to begin running, or any other higher level functional activity, is a critical error since the postoperative time itself is not the primary element that will determine readiness to return to running or sport participation.

We advocate the use of objective criteria and the successful performance of specific tests to determine when an athlete is ready to being running. Grindem et al. [43] reported that the reinjury rate following ACL surgery can be significantly reduced by using objective RTS criteria. Using specific criteria to progress through the rehabilitation process assists not only in guiding the overall process, but more importantly it ensures progressing an athlete when they are physically capable, rather than based solely on some arbitrary time frame. The criteria we use to progress athletes through the rehabilitation process are presented in Table 15.2. The specific tests and measures we administer and the scores necessary to begin running are presented in Table 15.3. Using specific tests and predetermined criteria takes the subjective element out of athlete progression while providing the athlete with known measurable goals that must be achieved prior to progressing. This objective format serves both to motivate athletes and to eliminate as much of the guesswork as possible when answering the question, "when can I start running again?"

The last step in the sequential progression of ACL rehabilitation involves the restoration of function through sport-specific training directed toward returning the athlete to competition. Many of the previously discussed drills, such as cone drills, lunges with sport cords, plyometric drills, and the running and agility progression, can be modified for the specific functional movement patterns associated with the athlete's unique sport. Some sport-specific running and agility drills include side-shuffling, cariocas, sudden starts and stops, zigzags, 45° cutting, and 90° cutting. The specific movement patterns learned throughout the rehabilitation program must be progressively integrated to provide challenges in a controlled setting prior to any return-to-play activity.

Advancing functional activity needs to be more than just a return to running. Objective testing should include the following: isokinetic strength test [44, 71, 72], the International Knee Documentation Committee Subjective Knee Evaluation Form [73, 74], hop testing [75–77], ligamentous testing, functional testing such as a T shuttle run, Y balance test, functional movement screen, and other running tests. All of these have been advocated. In this process, the athlete must also demonstrate sufficient confidence in the affected extremity to successfully RTS without any fear or limitations [55, 78].

The complex nature of progressing an athlete back to unrestricted sport participation following ACL surgery should be, in and of itself, a complex progression of the key functional elements necessary for athletic performance. These elements should then be tested, measured, and advanced in a sequential, criteria-driven manner. Returning an athlete to participation should be a graduated continuum that progresses from the least demanding to most demanding activities, and not a single test or set of tests that releases an athlete to return to participation at any one single point in time.

We incorporate a battery of tests applied in a sequential five-phased performance assessment. This assessment is designed to determine activity readiness prior to the introduction of demanding functional athletic elements, reduce the risk of reinjury or contralateral injury, and promote psychological confidence. This program rank-orders the relative demand of functional activities required for athletic participation and guides advancement back to unlimited activity via defined criteria to determine readiness for five key athletic elements: running, agility drills, jumping, hopping/cutting, and unrestricted sport. The tests performed and the criteria to progress to each of these athletic elements are presented in Table 15.3.

This type of performance progression assessment testing provides the clinician with a useful

Table 15.3 ACLR performance progression assessment

Goals	Tests	Criteria
Group A tests: clearance to begin running (treadmill jogging)	1. IKDC Subjective Knee Evaluation Form: Score_____ Pass_____ Fail_____ 2. CKRS Symptom rating: Score_____ Pass_____ Fail_____ 3. 30 step-and-holds (forward jump-lunge and landing): Pass_____ Fail_____ 4. 10 single-leg squats to 45°: Pass_____ Fail_____ 5. 1-RM on leg press: inv/nonin = _____/_____=_____ 6. 15-min fast treadmill walking: Pass_____ Fail_____ 7. KT-1000 or KT-2000 test (or clinical Lachman test): Side-to-side difference _____ 8. Isokinetic testing (or handheld dynamometer if available): Pass_____ Fail_____ Group A test summary: PASS FAIL Rationale for failure:	IKDC score = 90 CKRS symptom score = 10 30 step-and-holds without loss of balance or excessive motion outside sagittal plane 10 consecutive single-leg squats without loss of balance or excessive motion outside sagittal plane ≥70% 1-RM leg press inv/noninv Treadmill walking: normal gait pattern for entire 15 min KT <2 mm inv/nonin Isokinetic fulfills criteria for quadriceps peak torque/body weight (BW) ratio, ham/quad (H/Q) ratio, bilateral peak torque comparison[a]
Group B tests: clearance to begin low-level agility drills	1. IKDC Subjective Knee Evaluation Form: Score_____ Pass_____ Fail_____ 2. CKRS Symptom Rating: Score_____ Pass_____ Fail_____ 3. 10 single-leg squats to 45° with weight: Inv/nonin = _____/_____=_____ 4. 1-RM on leg press: inv/nonin = _____/_____=_____ 5. Run 1 mile on treadmill: Pass_____ Fail_____ 6. KT-1000 or KT-2000 test (or clinical Lachman test): Side-to-side difference _____ 7. Isokinetic testing (or handheld dynamometer): Pass_____ Fail_____ 8. Single-leg hop tests (single-leg hop for distance, timed 6 m hop, triple cross-over hop): Inv/nonin = _____/_____=_____ Inv/nonin = _____/_____=_____ Inv/nonin = _____/_____=_____ Inv/nonin = _____/_____=_____ Pass_____ Fail_____ Group B test summary: PASS FAIL Rationale for failure:	IKDC score = 90 CKRS symptom score = 10 10 consecutive single-leg squats without loss of balance or excessive motion outside sagittal plane while holding ≥75% weight (dumbbells, weight vest, etc.) >80% 1-RM leg press inv/nonin Normal running pattern on the treadmill KT <2 mm inv/nonin (values same as prior tests) Isokinetic fulfills criteria for quadriceps peak torque/BW ratio, H/Q ratio, bilateral peak torque comparison[a] > 85% hop tests inv/nonin

(continued)

Table 15.3 (continued)

Goals	Tests	Criteria
Group C tests: clearance to begin jumping	1. IKDC Subjective Knee Evaluation Form: Score_____ Pass_____ Fail_____ 2. CKRS Symptom Rating: Score_____ Pass_____ Fail_____ 3. 10 single-leg squats to 60° with weight: Inv/nonin = _____/_____=_____ 4. 10-RM on leg press: inv/nonin = _____/_____=_____ 5. Lateral shuffle, forward/backward shuttle run, and carioca: Pass_____ Fail_____ 6. KT-1000 or KT-2000 test (or clinical Lachman test): Side-to-side difference _____ 7. Isokinetic testing (or handheld dynamometer): Pass_____ Fail_____ 8. Single-leg hop tests (single-leg hop for distance, timed 6 m hop, triple cross-over hop): Inv/nonin = _____/_____=_____ Inv/nonin = _____/_____=_____ Inv/nonin = _____/_____=_____ Inv/nonin = _____/_____=_____ Pass_____ Fail_____ Group C test summary: PASS FAIL Rationale for failure:	IKDC score = 90 CKRS symptom score = 8 10 consecutive single-leg squats without loss of balance or excessive motion outside sagittal plane while holding ≥85% weight (dumbbells, weight vest, etc.) ≥85% 10-RM leg press inv/nonin No compensation patterns with deceleration during agility drills KT <2 mm inv/noninv (values same as prior tests) Isokinetic fulfills criteria for quadriceps peak torque/BW ratio, H/Q ratio, bilateral peak torque comparison, endurance values, work fatigue values[a] >85% hop tests inv/nonin
Group D tests: clearance to begin hopping and cutting	1. IKDC Subjective Knee Evaluation Form: Score_____ Pass_____ Fail_____ 2. CKRS Symptom rating: Score_____ Pass_____ Fail_____ 3. 10 single-leg squats to 60° with weight: Inv/nonin = _____/_____=_____ 4. 10-RM on leg press: inv/nonin = _____/_____=_____ 5. Forward, lateral, and rotational jumps: Pass_____ Fail_____ 6. KT-1000 or KT-2000 test (or clinical Lachman test): Side-to-side difference _____ 7. Isokinetic testing (or handheld dynamometer): Pass_____ Fail_____ 8. Single-leg hop tests (single-leg hop for distance, timed 6 m hop, triple cross-over hop): Inv/nonin = _____/_____=_____ Inv/nonin = _____/_____=_____ Inv/nonin = _____/_____=_____ Inv/nonin = _____/_____=_____ Pass_____ Fail_____ Group D test summary: PASS FAIL Rationale for failure:	IKDC score = 90 CKRS symptom score = 8 10 consecutive single-leg squats without loss of balance or excessive motion outside sagittal plane while holding ≥90% weight (dumbbells, weight vest, etc.) ≥90% 1-RM on leg press No genu valgum when loading into or landing from jumps AND equal weight distribution when initiating and landing the jumps KT test <2 mm inv/noninv (values same as prior tests) Isokinetic fulfills criteria for quadriceps peak torque/BW ratio, H/Q ratio, bilateral peak torque comparison, endurance values, work fatigue values[a] >90% hop tests inv/nonin

Table 15.3 (continued)

Goals	Tests	Criteria
Clearance for return to sport		IKDC score = 90 CKRS symptom score = 8 Achieves ≥90% on all strength assessments Displays a normal running pattern that does not increase pain Has practiced and displays no hesitation or compensation strategies during agility drills (particularly when decelerating) when performed at 100% effort Has practiced and displays normal loading (no genu valgum) and soft, athletic landings from all jumps and hops Has practiced and displays no hesitation or compensation strategies during cutting drills (particularly when decelerating) when performed at 100% effort KT test values remain unchanged Fulfills isokinetic testing criteria[a] >90% on hop tests

[a]Isokinetic test criteria: quadriceps peak torque/BW ratio 180°/s: males >65%, females >55%; H/Q ratio 180°/s: males 66–72%, females 72–78%; bilateral comparison: quadriceps >85%, hamstrings >90%; endurance ratio 300°/s: quadriceps <15%, hamstrings <10%; no pain during test

BW body weight, *CKRS* Cincinnati knee rating system, *H/Q* hamstrings/quadriceps, *IKDC* International Knee Documentation Committee, *inv/noninv* involved/noninvolved, *KT* knee arthrometer, *RM* repetition maximum

set of tools to determine when an athlete is able to safely progress into higher-level sports drills and return to unrestricted athletic activities. In addition, it may provide incentive for athletes who require additional strength and neuromuscular retraining to progress functionally. The testing battery we use purposely incorporates a subjective analysis, conducted by the clinician, regarding the athlete's running, hopping, jumping/landing, and cutting maneuvers. A lack of athlete confidence or any compensation strategies used during these tasks indicates a need for continued training and counseling prior to returning to advancing functionally.

15.3 Conclusions

RTS is the last piece of the long 6–12 month process of returning an athlete to unrestricted activity. It neither happens automatically or accidentally. It is brought to fruition by a lot of hard work, effort, and the successful completion of critical steps accomplished throughout the rehabilitative process. The return to athletics needs to address the physical and also the mental aspect of the patient's level of function. Each of these steps acts as a building block working in concert, fitting together as pieces of a puzzle, to progressively restore the athlete's preinjury function and athletic ability.

This road takes an athlete from their injury, to a diagnosis, surgical intervention, and over an extensive course of rehabilitation designed to systematically and progressively advance the injured athlete back to function—progressing their athletic activities, returning them to training, and finally at the end of this long road, allowing them to take that final step back onto their field of play.

References

1. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. Am J Sports Med. 2011;39(3):538–43. https://doi.org/10.1177/0363546510384798.
2. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. Br J Sports Med. 2011;45(7):596–606. https://doi.org/10.1136/bjsm.2010.076364.
3. Brophy RH, Gill CS, Lyman S, Barnes RP, Rodeo SA, Warren RF. Effect of anterior cruciate ligament reconstruction and meniscectomy on length of career in National Football League athletes: a case control study. Am J Sports Med. 2009;37(11):2102–7. https://doi.org/10.1177/0363546509349035.
4. Busfield BT, Kharrazi FD, Starkey C, Lombardo SJ, Seegmiller J. Performance outcomes of anterior cruciate ligament reconstruction in the National Basketball Association. Arthroscopy. 2009;25(8):825–30. https://doi.org/10.1016/j.arthro.2009.02.021.
5. Carey JL, Huffman GR, Parekh SG, Sennett BJ. Outcomes of anterior cruciate ligament injuries to running backs and wide receivers in the National Football League. Am J Sports Med. 2006;34(12):1911–7. https://doi.org/10.1177/0363546506290186.
6. Shah VM, Andrews JR, Fleisig GS, McMichael CS, Lemak LJ. Return to play after anterior cruciate ligament reconstruction in National Football League athletes. Am J Sports Med. 2010;38(11):2233–9. https://doi.org/10.1177/0363546510372798.
7. Wilk KE. Anterior cruciate ligament injury prevention and rehabilitation: let's get it right. J Orthop Sports Phys Ther. 2015;45(10):729–30. https://doi.org/10.2519/jospt.2015.0109.
8. Buller LT, Best MJ, Baraga MG, Kaplan LD. Trends in anterior cruciate ligament reconstruction in the United States. Orthop J Sports Med. 2015;3(1):2325967114563664. https://doi.org/10.1177/2325967114563664.
9. Woby SR, Roach NK, Urmston M, Watson PJ. Psychometric properties of the TSK-11: a shortened version of the Tampa Scale for Kinesiophobia. Pain. 2005;117(1-2):137–44. https://doi.org/10.1016/j.pain.2005.05.029.
10. Noyes FR, Mangine RE, Barber S. Early knee motion after open and arthroscopic anterior cruciate ligament reconstruction. Am J Sports Med. 1987;15(2):149–60.
11. Shelbourne KD, Nitz P. Accelerated rehabilitation after anterior cruciate ligament reconstruction. Am J Sports Med. 1990;18(3):292–9.
12. Mangine RE, Noyes FR. Rehabilitation of the allograft reconstruction. J Orthop Sports Phys Ther. 1992;15(6):294–302.
13. Shelbourne KD, Wilckens JH, Mollabashy A, DeCarlo M. Arthrofibrosis in acute anterior cruciate ligament reconstruction. The effect of timing of reconstruction and rehabilitation. Am J Sports Med. 1991;19(4):332–6.
14. Wilk KE, Andrews JR. Current concepts in the treatment of anterior cruciate ligament disruption. J Orthop Sports Phys Ther. 1992;15(6):279–93. https://doi.org/10.2519/jospt.1992.15.6.279.
15. Wilk KE, Reinold MM, Hooks TR. Recent advances in the rehabilitation of isolated and combined anterior cruciate ligament injuries. Orthop Clin North Am. 2003;34(1):107–37.
16. Cosgarea AJ, Sebastianelli WJ, DeHaven KE. Prevention of arthrofibrosis after anterior cruciate ligament reconstruction using the central third patellar tendon autograft. Am J Sports Med. 1995;23(1):87–92.
17. Fu FH, Woo SLY, Irrgang JJ. Current concepts for rehabilitation following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 1992;15(6):270–8. https://doi.org/10.2519/jospt.1992.15.6.270.
18. Salter RB, Simmonds DF, Malcolm BW, Rumble EJ, MacMichael D, Clements ND. The biological effect of continuous passive motion on the healing of full-thickness defects in articular cartilage. An experimental investigation in the rabbit. J Bone Joint Surg Am. 1980;62(8):1232–51.
19. Wilk KE, Andrews JR, Clancy WG. Anterior cruciate ligament reconstruction rehabilitation - the results of aggressive rehabilitation: a 12-week follow-up in 212 cases. Isokinet Exerc Sci. 1992;2:82–91.
20. Sachs RA, Reznik A, Daniels DM. Chapter 28: Complications of knee ligament surgery. In: Daniel D, editor. Knee ligaments: structure, function, injury, and repair. New York: Raven; 1990.
21. Wilk KE, Arrigo C, Andrews JR, Clancy WG. Rehabilitation after anterior cruciate ligament reconstruction in the female athlete. J Athl Train. 1999;34(2):177–93.
22. Lephart S, Kocher MS, Fu F, Borsa PA, Harner CD. Proprioception following anterior cruciate ligament reconstruction. J Sport Rehabil. 1992;1:188–96.
23. Lephart SM, Pincivero DM, Giraldo JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. Am J Sports Med. 1997;25(1):130–7.
24. Howe JG, Johnson RJ, Kaplan MJ, Fleming B, Jarvinen M. Anterior cruciate ligament reconstruction using quadriceps patellar tendon graft. Part I. Long-term followup. Am J Sports Med. 1991;19(5):447–57.
25. Millett PJ, Wickiewicz TL, Warren RF. Motion loss after ligament injuries to the knee. Part II: prevention and treatment. Am J Sports Med. 2001;29(6):822–8.
26. Millett PJ, Wickiewicz TL, Warren RF. Motion loss after ligament injuries to the knee. Part I: causes. Am J Sports Med. 2001;29(5):664–75.

27. Shelbourne KD, Gray T. Anterior cruciate ligament reconstruction with autogenous patellar tendon graft followed by accelerated rehabilitation. A two- to nine-year followup. Am J Sports Med. 1997;25(6):786–95.
28. Austin JC, Phornphutkul C, Wojtys EM. Loss of knee extension after anterior cruciate ligament reconstruction: effects of knee position and graft tensioning. J Bone Joint Surg Am. 2007;89(7):1565–74.
29. Harner CD, Irrgang JJ, Paul J, Dearwater S, Fu FH. Loss of motion after anterior cruciate ligament reconstruction. Am J Sports Med. 1992;20(5):499–506.
30. Irrgang JJ, Harner CD. Loss of motion following knee ligament reconstruction. Sports Med. 1995;19(2):150–9.
31. Rubin LE, Yeh PC, Medvecky MJ. Extension loss secondary to femoral-sided inverted cyclops lesion after anterior cruciate ligament reconstruction. J Knee Surg. 2009;22(4):360–3.
32. Benum P. Operative mobilization of stiff knees after surgical treatment of knee injuries and posttraumatic conditions. Acta Orthop Scand. 1982;53(4):625–31.
33. Blazevich AJ, Cannavan D, Horne S, Coleman DR, Aagaard P. Changes in muscle force-length properties affect the early rise of force in vivo. Muscle Nerve. 2009;39(4):512–20. https://doi.org/10.1002/mus.21259.
34. Knight KL, Martin JA, Londeree BR. EMG comparison of quadriceps femoris activity during knee extension and straight leg raises. Am J Phys Med. 1979;58(2):57–67.
35. Perry J, Antonelli D, Ford W. Analysis of knee joint forces during flexed-knee stance. J Bone Joint Surg. 1975;57A(7):961–7.
36. Ahmad CS, Kwak SD, Ateshian GA, Warden WH, Steadman JR, Mow VC. Effects of patellar tendon adhesion to the anterior tibia on knee mechanics. Am J Sports Med. 1998;26(5):715–24. https://doi.org/10.1177/03635465980260051901.
37. McClure PW, Blackburn LG, Dusold C. The use of splints in the treatment of joint stiffness: biologic rationale and an algorithm for making clinical decisions. Phys Ther. 1994;74(12):1101–7.
38. Shelbourne KD, Gray T. Minimum 10-year results after anterior cruciate ligament reconstruction: how the loss of normal knee motion compounds other factors related to the development of osteoarthritis after surgery. Am J Sports Med. 2009;37(3):471–80. https://doi.org/10.1177/0363546508326709.
39. Dye SF, Chew MH. Restoration of osseous homeostasis after anterior cruciate ligament reconstruction. Am J Sports Med. 1993;21(5):748–50.
40. Atkinson TS, Atkinson PJ, Mendenhall HV, Haut RC. Patellar tendon and infrapatellar fat pad healing after harvest of an ACL graft. J Surg Res. 1998;79(1):25–30.
41. Paulos LE, Rosenberg TD, Drawbert J, Manning J, Abbott P. Infrapatellar contracture syndrome. An unrecognized cause of knee stiffness with patella entrapment and patella infera. Am J Sports Med. 1987;15(4):331–41.
42. Palmieri-Smith RM, Lepley LK. Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. Am J Sports Med. 2015;43(7):1662–9. https://doi.org/10.1177/0363546515578252.
43. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med. 2016;50(13):804–8. https://doi.org/10.1136/bjsports-2016-096031.
44. Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. J Orthop Sports Phys Ther. 1994;20(2):60–73.
45. Draper V, Ballard L. Electrical stimulation versus electromyographic biofeedback in the recovery of quadriceps femoris muscle function following anterior cruciate ligament surgery. Phys Ther. 1991;71(6):455–61; discussion 461-454.
46. Kim KM, Croy T, Hertel J, Saliba S. Effects of neuromuscular electrical stimulation after anterior cruciate ligament reconstruction on quadriceps strength, function, and patient-oriented outcomes: a systematic review. J Orthop Sports Phys Ther. 2010;40(7):383–91. https://doi.org/10.2519/jospt.2010.3184.
47. Wilk KE, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR, Boyd ML. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. Am J Sports Med. 1996;24(4):518–27.
48. Barrack RL, Skinner HB, Buckley SL. Proprioception in the anterior cruciate deficient knee. Am J Sports Med. 1989;17(1):1–6.
49. Barrett DS. Proprioception and function after anterior cruciate reconstruction. J Bone Joint Surg. 1991;73B(5):833–7.
50. Beard DJ, Dodd CAF, Trundle HR, Simpson AHRW. Proprioception enhancement for anterior cruciate ligament deficiency. A prospective randomised trial of two physiotherapy regimes. J Bone Joint Surg. 1994;76B(4):654–9.
51. Beard DJ, Kyberd PJ, Dodd CA, Simpson AH, O'Connor JJ. Proprioception in the knee. J Bone Joint Surg Br Vol. 1994;76(6):992–3.
52. Markolf KL, Graff-Radford A, Amstutz HC. In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. J Bone Joint Surg Am. 1978;60(5):664–74.
53. Paterno MV, Myer GD, Ford KR, Hewett TE. Neuromuscular training improves single-limb stability in young female athletes. J Orthop Sports Phys Ther. 2004;34(6):305–16.
54. Fitzgerald GK, Axe MJ, Snyder-Mackler L. The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physical active individuals. Phys Ther. 2000;80(2):128–40.

55. Chmielewski TL, Jones D, Day T, Tillman SM, Lentz TA, George SZ. The association of pain and fear of movement/reinjury with function during anterior cruciate ligament reconstruction rehabilitation. J Orthop Sports Phys Ther. 2008;38(12):746–53. https://doi.org/10.2519/jospt.2008.2887.
56. Lattanzio PJ, Petrella RJ, Sproule JR, Fowler PJ. Effects of fatigue on knee proprioception. Clin J Sport Med. 1997;7(1):22–7.
57. Lattanzio PJ, Petrella RJ. Knee proprioception: a review of mechanisms, measurements, and implications of muscular fatigue. Orthopedics. 1998;21(4):463–70; discussion 470-461; passim.
58. Skinner HB, Wyatt MP, Hodgdon JA, Conard DW, Barrack RL. Effect of fatigue on joint position sense of the knee. J Orthop Res. 1986;4(1):112–8.
59. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med. 1999;27(6):699–706.
60. Hewett TE, Myer GD, Ford KR, Heidt RS Jr, Colosimo AJ, McLean SG, van den Bogert AJ, Paterno MV, Succop P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med. 2005;33(4):492–501. https://doi.org/10.1177/0363546504269591.
61. Myer GD, Chu DA, Brent JL, Hewett TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. Clin Sports Med. 2008;27(3):425–48, ix. https://doi.org/10.1016/j.csm.2008.02.006.
62. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. Am J Sports Med. 2007;35(7):1123–30.
63. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. Am J Sports Med. 2007;35(3):368–73.
64. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med. 1996;24(6):765–73.
65. Hewett TE. Predisposition to ACL injuries in female athletes versus male athletes. Orthopedics. 2008;31(1):26–8.
66. Renstrom P, Ljungqvist A, Arendt E, Beynnon B, Fukubayashi T, Garrett W, Georgoulis T, Hewett TE, Johnson R, Krosshaug T, Mandelbaum B, Micheli L, Myklebust G, Roos E, Roos H, Schamasch P, Shultz S, Werner S, Wojtys E, Engebretsen L. Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. Br J Sports Med. 2008;42(6):394–412. https://doi.org/10.1136/bjsm.2008.048934.
67. Joseph M, Tiberio D, Baird JL, Trojian TH, Anderson JM, Kraemer WJ, Maresh CM. Knee valgus during drop jumps in National Collegiate Athletic Association Division I female athletes: the effect of a medial post. Am J Sports Med. 2008;36(2):285–9. https://doi.org/10.1177/0363546507308362.
68. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. J Orthop Sports Phys Ther. 2010;40(2):42–51. https://doi.org/10.2519/jospt.2010.3337.
69. Wilk KE, Reinold MM. Plyometric and closed kinetic chain exercise. In: Brandy WD, editor. Therapeutic exercises: techniques for intervention. Philadelphia, PA: Lippincott, Williams and Wilkins; 2001.
70. Wilk KE, Voight ML, Keirns MA, Gambetta V, Andrews JR, Dillman CJ. Stretch-shortening drills for the upper extremities: theory and clinical application. J Orthop Sports Phys Ther. 1993;17(5):225–39.
71. Gobbi A, Francisco R. Factors affecting return to sports after anterior cruciate ligament reconstruction with patellar tendon and hamstring graft: a prospective clinical investigation. Knee Surg Sports Traumatol Arthrosc. 2006;14(10):1021–8. https://doi.org/10.1007/s00167-006-0050-9.
72. Mattacola CG, Perrin DH, Gansneder BM, Gieck JH, Saliba EN, McCue FC 3rd. Strength, functional outcome, and postural stability after anterior cruciate ligament reconstruction. J Athl Train. 2002;37(3):262–8.
73. Higgins LD, Taylor MK, Park D, Ghodadra N, Marchant M, Pietrobon R, Cook C, International Knee Documentation Committee. Reliability and validity of the International Knee Documentation Committee (IKDC) Subjective Knee Form. Joint Bone Spine. 2007;74(6):594–9. https://doi.org/10.1016/j.jbspin.2007.01.036.
74. Mehta VM, Paxton LW, Fornalski SX, Csintalan RP, Fithian DC. Reliability of the international knee documentation committee radiographic grading system. Am J Sports Med. 2007;35(6):933–5.
75. Gustavsson A, Neeter C, Thomee P, Silbernagel KG, Augustsson J, Thomee R, Karlsson J. A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2006;14(8):778–88. https://doi.org/10.1007/s00167-006-0045-6.
76. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med. 1991;19(5):513–8.
77. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. Phys Ther. 2007;87(3):337–49.
78. Webster KE, Feller JA, Lambros C. Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. Phys Ther Sport. 2008;9(1):9–15. https://doi.org/10.1016/j.ptsp.2007.09.003.

16 Neuroscience Principles for ACL Rehabilitation and Reinjury Risk Reduction

James Onate, Daniel Herman, Dustin Grooms, Zach Sutton, and Gary Wilkerson

16.1 Anterior Cruciate Ligament Injury

An anterior cruciate ligament (ACL) rupture is a debilitating activity-related knee injury that usually requires surgical reconstruction and extensive rehabilitation to restore knee stability and function [1–3]. The current best evidence suggests that targeting the neuromuscular control system is the key to effective rehabilitation to restore patient function and reduce reinjury risk [4, 5]. The current standard of care for ACL post-surgical rehabilitation is to engage in neuromuscular training, yet a failure rate up to 25% remains following return to activity in young active individuals [6–8]. This high failure rate is further compounded by the majority of individuals not even returning to preinjury levels of activity [9]. This leaves an opportunity to improve current neuromuscular training interventions

J. Onate
OSU Division of Athletic Training, The Ohio State University, Columbus, OH, USA

OSU Movement Optimization Prevention for Exercise Sustainment (MOvES), The Ohio State University, Columbus, OH, USA

OSU Movement Analysis & Performance Research Program, The Ohio State University, Columbus, OH, USA

Stanley D. and Joan H. Ross Center for Brain Health & Performance, The Ohio State University, Columbus, OH, USA

OSU Sports Medicine Research Institute, The Ohio State University, Columbus, OH, USA

OSU Human Performance Collaborative, The Ohio State University, Columbus, OH, USA
e-mail: Onate.2@osu.edu

D. Herman
Divisions of PM&R, Sports Medicine, and Research, Department of Orthopedics and Rehabilitation, University of Florida, Gainesville, FL, USA
e-mail: Hermadc@ortho.ufl.edu

D. Grooms
Athletic Training, Ohio University, Athens, OH, USA

School Applied Health Sciences & Wellness, Ohio University, Athens, OH, USA

College of Health Sciences and Professions, Ohio University, Athens, OH, USA

Ohio Musculoskeletal & Neurological Institute, Ohio University, Athens, OH, USA
e-mail: groomsd@ohio.edu

Z. Sutton
Health Rehabilitation Centers, University of Florida, Gainesville, FL, USA

G. Wilkerson (✉)
University of Tennessee at Chattanooga, Chattanooga, TN, USA
e-mail: Gary-Wilkerson@utc.edu

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_16

to ensure return to physical activity levels with optimal outcomes and reduced second injury risk [10–14].

Although evidence supports neuromuscular training for effective injury prevention and rehabilitation, many of these approaches primarily target biomechanical factors such as muscle strength, balance, and plyometric function with less consideration for cognitive or neurological components [4, 5, 15, 16]. While rectifying the biomechanical profile and restoring muscle strength are vital components of the rehabilitation process, there may be potential to further improve function and decrease reinjury risk [17, 18]. Recent reports demonstrate unresolved neuroplastic alterations after injury, reconstruction, and rehabilitation that may be limiting function and the return to sport (RTS) participation [19–21]. These data stem from the foundational concept that the ACL is not only an intra-articular ligament providing mechanical stability to the knee joint, but is also highly innervated with mechanoreceptors that provide afferent signals to the central nervous system (CNS) and injury/reconstruction causes the loss of these mechanoreceptors [22–24]. A simple analogy for ACL reconstruction (ACLR) is that a torn electrical cord can be appropriately put back together, but the cord does not properly conduct electricity in its previous fashion. By targeting cognitive-associated neurological factors during neuromuscular rehabilitation progressions, it may be possible to improve the transfer of sensorimotor adaptations from the clinic to activity, and ultimately improve patient outcomes [25, 26].

16.2 Limitations of the Classic Structural-Mechanical Model

The very nature of the noncontact ACL injury mechanism illustrates the vital role of the CNS to restore function and prevent second ACL injury [27, 28]. The noncontact ACL mechanism is due to a loss of neuromuscular control during activities that can range from simple running to jump-landing and rapid direction changes [29–31]. This noncontact injury scenario demonstrates the need to challenge a broad spectrum of sensorimotor control contributions. The noncontact mechanism has repeatedly been associated with a failure to maintain knee neuromuscular control, while attending to an external focus of attention, involving highly complex dynamic visual stimuli, variable surfaces, movement planning, rapid decision-making, variable player positions and environment interactions, and unanticipated perturbations [32–35].

While many factors, including hormonal [36, 37], gender [38, 39], anatomical [40–43], and even genetic [44–46] influences, have been implicated in injury risk, the primary focus of physical rehabilitation has been dynamic neuromuscular control, since it is modifiable [5, 15, 16, 47–51] and a prospective predictor of primary [52–55] and secondary [7] injury. A great deal of evidence suggests targeting the neuromuscular control system is the key to intervention effectiveness, and the ability to mitigate injury risk may be to optimize the biomechanical-neurological integrated system [4, 5, 48, 56]. However, despite a great deal of biomechanical data to support altered movement strategies that continue to exist despite intervention, orthopedic medicine has only just begun to examine how joint injury influences the nervous system.

Recent research has demonstrated that CNS changes may be more important to sustained optimization of movement strategies than reliance on biomechanical post-test measures alone [21, 57–63]. This suggests that the CNS underlies any modification of injury risk, and to decrease risk, a motor control adaptation is required to adjust the requisite neuromuscular and biomechanically measured change [47, 61, 64–66]. The sustainment of movement strategies to reduce injury risk is highly associated with a neuroplastic motor learning adaptation [67–71]. However, due to limitations of the biomechanical model of musculoskeletal injury assessment, current interventions focus on adaptations made in primarily biomechanical terms that have been shown to revert to pre-intervention levels or not induce improvement at all [10, 12, 66, 72–74].

Current standard of care interventions that target the neuromuscular control system may be missing vital aspects of sensorimotor function because significant deficits in neuromuscular function remain during RTS [4, 5, 75–77]. The best practice neuromuscular control focused programs may be insufficient to fully address reinjury risk or restore patient function [7, 12, 64, 78–80]. It is likely that aspects of sensorimotor function that are affected by the injury are not adequately addressed in therapy, allowing suboptimal neuroplastic compensations to occur [81–83]. Consideration of neurological post-injury adaptations, in addition to restoring mechanical stability, is needed to formulate adjunct therapeutic strategies to improve neuromuscular control.

16.3 Neuromuscular Control

The term neuromuscular control is meant to encompass a spectrum of human function, ranging from the afferent input, the processing of that input, generation of the efferent output, and the overall coordination of the system [84]. Neuromuscular control also has a temporal component in the continuous feedback loops between sensory and motor processing that contribute to the final measurable output [85]. As the muscles contract and bodily segments move, the afferent system is constantly sending new signals to the motor system to update the position, force generation, environmental representation, and other factors relative to the output. This constantly updating system represents the neuromuscular control profile so important to movement control and performing motoric tasks.

To experimentally capture the neuromuscular control system, a largely behaviorist and functionalist methodology has dominated the field with reliance on a postural-structural-biomechanical approach [86]. This prevailing method is concerned primarily with measuring the final output of the system in the form of joint biomechanics without any quantification of the underlying mechanisms that generate those mechanics [9, 87]. This behaviorist or outcome-oriented approach does not account for the extensive neural computations associated with sensory processing along vestibular, visual, and somatosensory pathways which in turn allow for stability and control in the presence of a changing environment [87, 88]. The proprioception, force control, and kinesthetic contributions of the sensory system are vital to the organization of motor output and maintaining neuromuscular control integrity [88]. The ACL is unique compared to most ligamentous structures in that it has robust afferent connections with the spinal cord [89, 90] and cerebrum [24, 91]. This is due to the high volume of mechanoreceptors such as free nerve endings, Ruffini end organs, Pacinian corpuscles, and Golgi receptors in the synovial lining of the ACL that contribute a great deal to afferent function [92–96]. Restoration of these important neurological features has not been well established in the clinical setting, yet may prove to be vitally important to the future function post ACL injury.

The interaction between proprioceptive inputs, such as that from the ACL, and visual input plays a crucial role in providing overall afferent input to the CNS to regulate movement control feedback loops [88, 97–100]. The brain receives somatosensory information in the thalamus and primary somatosensory cortex (via Brodmann's areas 3-1-2), and then integrates that afferent information caudally in the posterior parietal cortex, areas 5 and 7. This is also where the temporal lobe processed vestibular and visual information integrates with somatosensation before transmitting to the premotor cortex (area 8) and finally to the motor cortex (area 6) to achieve motor drive [85].

Musculoskeletal injuries may alter this flow of somatosensory [19, 81, 101–103], vestibular [104–106], and visual [82, 107, 108] processing in the CNS to sustain motor control. To maintain neuromuscular integrity in the presence of joint injury, the CNS may compensate with altered motor planning [105], regulation of integrated sensory information reaching the motor areas [19, 101], increased reliance on visual feedback or memory [82, 109], and/or alter the cortical-spinal drive [110, 111]. This CNS functional reorganization is most likely due to the mechanoreceptors lost in the damaged tissue contributing to decreased afferent input [92, 93]. This diminished sensory function is present despite years after the injury and normalized strength of the surrounding musculature [81, 83]. This is a likely source of neuroplasticity post musculoskeletal injury; thus, examining methods to address the sensory-visual-motor system along with the neuromuscular system in rehabilitation may improve patient function and decrease recurrent injury risk.

16.4 Neuromechanical Principles of Performance and Injury Risk

Action is the expression of cognitive processes [112], which integrate expectations derived from previous experiences with perceptions of changing conditions in both internal to the body and with respect to the external environment [113]. The term *perception-action coupling* refers to the interdependent nature of neural processes that link sensory inputs to motor outputs [113–116]. The efficiency of perception-action coupling may also be referred to as *neuromechanical coupling*, which has specifically been related to supraspinal modulation in muscle tone to create an optimal state of readiness to respond [117]. Thus, the term *neuromechanical responsiveness* is a designation for the combination of neurocognitive and biomechanical factors that influence the effectiveness of neuromuscular responses to rapidly changing environmental circumstances [118].

A list of common neurocognitive dimensions important to neuromechanical responsiveness can be found in Table 16.1. Vision is the source of sensory input that is primarily relied upon to make decisions about alternative responses to a given external environmental scenario [119], but cognitive processes that interpret visual inputs do not necessarily produce an internal representation that perfectly reproduces every element of the actual scene [120]. Visual-spatial working memory is required to synthesize discrete "snapshot" visual inputs for brain perception of a continuous stream of visual information, with processing informed by memories of past experiences in similar scenarios [121]. Simultaneously, an athlete will process a continuous stream of internal sensory information regarding motor performance, such as balance, proprioception, and force output. The athlete is not only required to attend to these different streams of information simultaneous (i.e., dual-tasking), but typically must be able to process and react as fast as possible in order to maximize their task performance. Because the brain of a given individual provides finite neural resources, rapidly changing circumstances in a highly demanding situation can require selective attention to a limited number of key information processing requirements [119–122]. If cognitive load exceeds neural processing capacity, an athlete may be required to narrow the range of sensory information to which they attend. This may result in "blindness" to unattended visual stimuli or inattention to errors in motor control output [123]. Conversely, when a primary focus of attention does not exhaust processing resources, a larger scope of sensory stimuli may be used to maximize performance [124]. The relative levels of cognitive demand during an athletic task and the cognitive capacity of the athlete may contribute to the overall injury risk of the athlete.

A practical example of this dynamic may be seen in the case of a running back in American football who is attempting to advance the ball downfield. The running back must use visual and spatial cognitive resources to attend to an evolving field of play, such as the location of his blocking linemen, the angles of pursuit of opposing linebackers, and his own position relative

Table 16.1 Dimensions of neurocognitive performance in the sport performance context

Dimension	Working definition
Visual attention	The ability to concentrate on visual input to the exclusion of other less essential stimuli
Self-monitoring	The ability to focus on proprioceptive kinesthetic feedback
Agility fine motor skill	The ability to make minor adjustments in motor activity
Processing speed/reaction time	The ability to engage in stimuli-response behavior within an intended time frame
Dual tasking	The ability to engage in two activities at the same time to maximize goal attainment

to the boundaries of play or first down marker. This information is continually compared to prior memory formed by practice of the play or prior game experience. At the same time, he is processing this external information, the running back is processing internal feedback of his own motor performance and interaction with the environment, such as a wet playing field, and then responding as needed to make alterations to his motor control. The player also needs to be able to process and react to these streams of information as fast as possible in order to maximize the yardage gained on the play. If there is a significant mismatch between his capacity for cognitive processing and the cognitive load imposed during task performance, the running back may be at increased risk for injury. This may manifest by a contact injury mechanism, whereby the running back is unable to adequately prepare to receive a hit in a safe manner from a player in his peripheral vision to whom he was unable to devote attentional resources. Similarly, this increased risk of injury could result from a noncontact mechanism, possibly due to a lack of attention to or errors in processing of internal feedback of motor control while prioritizing the processing of external sensory information.

This concept of neuromechanical responsiveness has been demonstrated in prior studies. Normal individuals ranging from military recruits to high-level collegiate football players who perform in the lower range of neurocognitive reaction time have been demonstrated to be at increased risk for musculoskeletal injuries [125, 126]. This effect has also been demonstrated with respect to ACL injury risk specifically, with one study finding that ACL-injured collegiate athletes demonstrated lower levels of preinjury performance across a range of neurocognitive domains, including visual and verbal memory, visual motor speed, and reaction time [127]. Similarly, biomechanical performance of athletic tasks associated with ACL injury risk has been shown to degrade with cognitive loading [128, 129], while athletes with poor memory, reaction time, and visual processing scores demonstrate worse biomechanical performance on biomechanical measures associated with an increased risk of ACL injury compared to athletes with good neurocognitive scores [130]. This relationship can be complicated by fatigue, which is a well-known risk factor for injury and has been shown to interact with cognitive demands to adversely affect the lower extremity biomechanics of female athletes during single-leg jump landing [114, 131]. Fatigue may exacerbate the adverse effects of other conditions or injuries on neural processing capacity, thereby increasing susceptibility to lapses in attention, distractibility, and inattentional blindness to environmental stimuli in the peripheral visual fields.

The dynamics of the relationship between cognition and biomechanics are further strained after ACL injury. Rupture of the ACL eliminates an important source of mechanoreceptor input to the CNS [24, 132, 133], and may have profound implications for maintenance of dynamic knee stability [117]. First, increased activation of brain areas that focus attention and process sensory information suggests that a greater volume of neural resources are required to control knee displacements [101]. Second, brain reweighting of sensory inputs increases reliance on vision for motor programming [107, 134], which has also been demonstrated in other ligamentous injuries such as chronic ankle instability [135]. These increased demands on neural resources may impose critical limitations on the ability to perform simultaneous visual, cognitive, and motor processes, thereby compromising neuromechanical responsiveness. Susceptibility to a poor functional outcome from an ACL injury or to a second ACL injury may be increased by low preinjury neurocognitive performance, the subsequent neural maladaptation from the injury, or a combination of the two [136, 137].

While brain activation patterns can exhibit dramatic changes following injury, activation patterns can similarly respond to training and open a new pathway for rehabilitation subsequent to ACL injury [138–142]. Training approaches may be used to enhance cognitive processing and diminish neural maladaptation from the injury. Due to the value of visual information during athletic tasks for performance purposes and the increased reliance on visual information in the absence of proprioceptive information from the

ACL, visual-cognitive training during rehabilitation may be important for the attainment of desirable neuroplastic adaptions. Choice responses to visual stimuli that involve whole-body movements may be advantageous for strengthening of functional connectivity that integrates neural networks for visual-cognitive and motor tasks [138–148]. Such functional network integration may explain enhanced automaticity of multitask responses that coincide with reduced neural activation of circuits linking the primary visual cortex, primary motor cortex, and cerebellum [139, 149, 150]. Thus, assessment and training activities should combine focused attention, visual stimulus discrimination for rapid decision making, and execution of compound motor skills [116, 150–152]. A number of computerized systems are now available to clinically assess and train the multiple interrelated aspects of neuromechanical responsiveness, including the capability for motion tracking of whole-body reactive responses to visual targets appearing within a virtual reality environment [58, 116, 152].

16.5 ACL Specific Neurological Adaptations

The overarching theory underpinning neuroplasticity from ACL injury is that the CNS afferent input is disrupted due to the lost somatosensory signals from the ruptured ligament and increased nociceptor activity associated with pain, swelling, and inflammation. The disrupted sensory input and injury-associated joint instability, muscle atrophy, and movement compensations combine to induce motor control adaptations. The reconstruction process leads to further deafferentation of the joint, causing continued neuroplastic modifications that result in maladapted efferent neuromuscular output [136].

In animal models, the ACL mechanoreceptor and afferent connections can be traced within the nervous system to the spinal cord, brain stem, and cerebral regions that contribute to proprioceptive, nociceptive, and reflex function [89, 91]. The initial sensorimotor neuroplasticity after ACL injury is likely caused by the abrupt loss of this connection that once provided the nervous system with continuous feedback [92–96, 153]. In human studies, the afferent loss is demonstrated by altered or absent somatosensory-evoked potentials with stimulation of the common peroneal nerve [24, 102, 103, 133] or, in surgery, of the ACL directly [154]. The loss of primary afferent information, combined with the pain and inflammatory responses, contributes to fundamentally alter the somatosensory feedback [107, 155–157]. The disrupted input, combined with mechanical changes and compensations [158, 159] (contralateral loading [80, 160], hip or ankle strategies [17, 161]), facilitates the adaptations for motor control [134, 162, 163]. On a foundational level, the altered motor output is displayed by disrupted gamma motor neuron function [163–165] and perturbation reflexes [162, 166] that play a key role in the ability to maintain neuromuscular integrity in a changing environment, requiring rapid and precise muscle stiffness or activation strategies [167–169]. The lost ability to rely on reflex and gamma motor neuron drive to prepare alpha motor neuron function requires the CNS to engage in supplementary mechanisms such as increased utilization of visual feedback to maintain the required sensory input for motor control [136, 170, 171]. As such, neuromuscular control after ACL injury may require enhanced visual feedback or memory reliance, depriving the CNS of resources once used for managing environmental interaction to maintain knee joint stability.

These deficits in neural function are not rectified with ACLR, as they may in fact become even more pronounced and/or present bilaterally [24, 110, 111, 165, 172–174]. The bilateral motor control, reflex, and proprioceptive changes are theorized to be due to both spinal [89, 91] and supraspinal [103, 175] mechanisms [176]. This ongoing neuroplasticity and altered mechanical and biological function of the joint combines to reduce proprioception acuity as measured by joint position sense [177, 178], movement detection [179, 180], and force sense [181]. To investigate the neurological adaptions of functional sensory loss, Baumeister et al. used electroencephalography (EEG), during force and joint sense tasks, and found that those with ACLR had greater brain activation in attentional and sensory areas [19, 101]. The increased activation may be attributed to less neural efficiency, or increased neural load to complete the same task; interestingly, despite increased cortical activation, proprioceptive performance was still worse in those with ACLR as compared to controls [19, 101]. These results indicate the loss of the native ACL not only constitutes a mechanical instability but a degree of nervous system deafferentation that is not rectified with reconstructive surgery and rehabilitation [153]. This partial deafferentation is further illustrated by investigations utilizing transcranial magnetic stimulation (TMS) to assess the CNS efferent pathway between the quadriceps and the brain [175, 177, 182, 183]. Heroux and Tremblay reported enhanced resting corticomotor excitability in those with ACL injury [182]. A potential mechanism for increased resting motor cortex excitability may be the altered sensory feedback, as the brain attempts to maintain motor output with attenuated sensory input. This increase in excitability may increase potential feed-forward mechanisms by decreasing the threshold for connections with motor planning areas, or allowing for increased input from other sensory sources (vision, vestibular) [184–187].

A neuroimaging investigation by Kapreli et al. [107] provided initial evidence of the neuroplastic effects of ACL injury. They performed functional magnetic resonance imaging (fMRI) of the brain during knee extension-flexion and found those with an ACL injury had increased activation of the pre-supplementary motor area, posterior secondary somatosensory area, and the posterior inferior temporal gyrus (pITG), compared to matched controls [107]. The pre-supplementary motor area is highly involved in complex motor planning [188, 189], and despite the relative simplicity of the movement task (single joint movement of 40° of knee extension-flexion while laying supine), those with an ACL injury needed to engage higher level motor control areas to a greater degree to execute the movement. This increased activation possibly indicates that on a neural-control level, simple movements are more taxing to those with a previous ACL injury [190]. The increase in posterior secondary somatosensory area provides further evidence of sensory-based neuroplasticity after injury, as this area is involved in regulating painful stimuli, but highly interconnected with the anterior secondary somatosensory area that integrates somatosensory inputs [169, 191, 192]. Interestingly, the participants in the study did not report pain during the movement, conceivably indicating a sensory processing adaptation from the initial increase in nociceptive input from the traumatic nature of the injury and not an acute effect. Alternatively, the prolonged nature of the rehabilitation, chronic pain, or joint instability may continue to disrupt typical somatosensory system afferent integration. The pITG plays a role in many cerebral functions [193, 194] but may primarily be involved with visual processing of movement [169]. As such, an increase in pITG activation during movement may indicate that in response to ACL injury there is an increased utilization of visual processing and motor-planning resources for movement concurrent with depression of somatosensory function [24, 82, 102, 103, 107, 133]. The findings of Kaperli et al. were also confirmed in ACLR patients with similar altered visual-motor and sensory-motor brain activation, potentially indicating shifts in cortical-subcortical processing and sensory reweighting [137, 171].

16.6 Neuroplasticity in Sport Rehabilitation

The transition from rehabilitation to sport activity is challenged by complex environmental interactions that place high demand on cognitive and sensorimotor processes and, in turn, increase ACL reinjury risk [32–35]. In a constantly changing environment, the primary afferent pathways (vestibular, visual, and somatosensory) interact to integrate and contextualize the feedback necessary for the efferent neuromuscular control system to maintain adequate stability and control [87, 88]. One area of sensorimotor function that may uniquely be affected by ACL injury is motor control requiring visual feedback [87]. The visual system provides a fundamental mechanism for coordination, regulation, and control of movement while managing environmental interactions (external focus) [109, 195, 196]. The need for visual feedback is especially true in executing movement sequences [189, 197] and with increases in task complexity and variability [196, 198–200]. The interplay between vision and somatosensation is particularly vital to provide sufficient afferent input to the CNS to regulate motor control and maintain neuromuscular integrity during action and environmental interaction [88, 97–100]. In this sensory-to-motor feedback loop, changes to visual or sensory feedback lead to subsequent alterations in neuromuscular control during movement (closed-loop processing) [23, 87, 88, 97, 99, 196].

Rehabilitative exercises are typically completed with an internal focus of control, meaning full attention is being directed to the internal aspects of the movement only (e.g., avoidance of excessive knee valgus or increasing knee flexion) [5, 22, 201]. Such an internal focus can offer positive benefits early in rehabilitation, when the need to develop or restore a motor pattern or muscle contraction ability is vital. However, function in the athletic environment, or even activities of daily living, requires constant interactions with the dynamic and constantly changing visual environment. Sport and activities of daily living, therefore, require an external focus of control, where attention is directed to the environment and the body relies on automatic motor control to maintain joint-to-joint integrity [200, 202, 203].

The need to challenge a broad spectrum of sensorimotor control is demonstrated by the noncontact ACL injury scenario itself: a failure to maintain knee neuromuscular control, while attending to an external focus of attention, involves highly complex dynamic visual stimuli, variable surfaces, movement planning, rapid decision-making, variable player positions and environment interactions, and unanticipated perturbations [32–35]. The need to bridge the intense neurocognitive and motor control demands of sport during rehabilitation may, therefore, benefit from specific interventions that target these neurological factors in addition to the biomechanical techniques that are already widely addressed.

Trauma to the ACL has been shown to modify how the nervous system processes the integration between vision and somatosensation [81, 82, 107, 108, 204]. By targeting injury-induced sensory-motor plasticity, a unique opportunity exists to improve the translation of neuromuscular system enhancements from the rehabilitation environment to the return to sport environment [58, 114, 131, 205]. The combined afferent neuroplasticity due to the lost mechanoreceptors of the ACL [94–96] and efferent neuroplasticity due to arthrogenic muscle inhibition [206] and disrupted gamma-motor neuron feedback loops [173] may induce specific central nervous system compensations. We have found that the CNS will increase reliance on visual feedback to program motion [136, 137, 171, 207–209]. Despite the injury, the nervous system continues to sustain motor output in the presence of depressed proprioceptive input [81, 82, 210] which may force increased use of visual-related feedback (memory or directly) by the motor cortex. This may also be partially induced, during rehabilitation, as therapy is strongly targeted at increased quadriceps activation immediately after surgery with a constant focus of attention on the knee joint; thus, the nervous system may create this visual-motor link during recovery.

Courtney et al. [102, 103, 162] in a series of works demonstrated that ACL-deficient individuals that went on to become copers (positive outcome without surgery) and adapted their movement strategy with increased hamstring activation to compensate for the instability had absent somatosensory-evoked potentials in the brain from the ACL. This was in opposition to noncopers or those that needed surgery or had a poor outcome having intact somatosensory-evoked potentials and no adaptation in motor control strategy. This work indicates that, if the brain does not receive the disrupted or absent afferent signal from a damaged ACL, no motor adaptation will occur. Any peripheral or spinal adaptations that mitigate the loss of the somatosensory-evoked potential at the brain actually resulted in a poorer outcome [211, 212]. This is further supported by recent work of Pietrosimone and colleagues who demonstrated that, after ACLR, those that have the lowest quadriceps activation failure, highest strength, and best reported outcomes have the greatest increase in cortical excitability [175, 178, 211, 212]. This may indicate that unique cortical mechanisms underpin recovery from injury and increased top-down and feedforward mechanisms can compensate to a degree the resulting instability and depressed afferent feedback form the injury.

16.7 ACL Injury Induced Sensory-Visual-Motor Processing Compensations

Neuroplastic observations following ACL injury are supported by biomechanical evidence, suggesting that with increased task complexity, neuromuscular control is deteriorated in individuals with an ACL injury or reconstruction to a greater extent than controls, possibly due to overload of motor planning resources [213, 214]. The specific neuroplastic visual-motor control adaptation is observed during static balance as those with ACL injury have significantly diminished postural control when vision is obstructed (blindfold or eyes closed) [108, 215], but limited to no degradation in postural control with eyes open, as they are able to use vision to compensate and maintain balance [216, 217]. A more pronounced effect on neuromuscular control is observed when disrupting visual-motor processing during complex landing and cutting maneuvers that play an even greater role in injury risk [218–220]. The simple addition of a target, during a jump-landing task, increased injury risk mechanics [221]and altered muscle activation, decreasing postural stability [222]. The effects of forcing visual focus on the environment during more complex cutting or direction change tasks further degrades neuromuscular control capability in healthy athletes with the addition of a defender [219], a virtual soccer interface [223], or a level of unanticipated decision making during the task (selecting direction) [224, 225]. The effect of occupying the visual system with environmental cues during landing or change of direction has an even greater effect on those with ACL injury history [28, 213]. Furthermore, adding an anticipatory component that integrates visual processing and reaction time further demonstrates a reduction in knee neuromuscular control [226]. The inclusion of short-term memory and online decision-making also demonstrates specific adaptations in the maintenance of joint-to-joint neuromuscular integrity during complex athletic maneuvers such as cutting or sidestepping [114, 225, 227–230]. Recently, examination of injury risk, comparing ball-handling or offensive action (considered anticipatory and feedforward in nature) vs. defending (considered unanticipatory and responsive in nature), demonstrated a higher risk with defensive action [231]. This large-scale epidemiological data further support the possible increased injury risk movement strategies when unanticipated, rapid decision-making and/or visual-motor feedback is altered during the laboratory biomechanical studies.

These findings, taken together, suggest that ACL injury may lead to a cascade of neuroplastic and neuromuscular alterations that increase reliance on visual feedback and cortical motor planning for the control of knee movement. The post-injury disrupted sensory feedback, combined with the observed motor compensations, contributes to fundamentally alter the CNS mechanisms for motor control [19, 24, 92, 94, 96, 101, 111, 133]. In attempting to regulate neuromuscular control in the presence of decreased somatosensory input, the nervous system supplements with increased motor planning, conscious cortical involvement, and greater reliance on visual feedback. This ACL injury induced neuroplasticity can have consequences for function and further injury risk as the visual feedback and motor planning neural mechanisms become overloaded in the athletic environment. Specific additions to current neuromuscular interventions, targeting these neuroplastic imbalances, may play a significant role to induce sensory-motor adaptations to decrease dependence on visual feedback when transitioning to more demanding activities [232, 233].

The application of neuroplastic constructs during neuromuscular rehabilitation to optimize musculoskeletal therapy interventions is a new frontier for orthopedic care. The opportunity to supplement traditional interventions by further targeting neuroplastic, cognitive, and visual-motor capabilities is an exciting time for research and clinical practice. These new approaches allow clinicians to approximate the neurocognitive demands of higher intensity athletic activity in a safe, controlled, and most importantly feedback rich environment before reintegration into sport. Recognition of the visual-motor implications in neuromuscular control, injury recovery, and prevention, combined with new technologies, may help to mitigate post-injury movement dysfunction and decrease injury risk when returning to activity.

The training, and even restoration, of primarily biomechanical factors relative to ACL injury risk [52, 234] may not be addressing all the physiologic consequences of the injury, as even years post injury, patient-reported dysfunction and poor movement control persist [79, 80, 83, 159, 235, 236]. The impaired physical performance and patient-reported dysfunction might in part have a neurological origin [107, 173, 175]. The capacity for neuroplasticity, after injury and during therapy, presents an avenue to close a gap between rehabilitation and activity by targeting a broader spectrum of sensorimotor function during neuromuscular training [12, 16, 64, 79]. Alternative approaches and adjunct therapies may help to address the neurological system functions associated with the faulty movement patterns underlying ACL reinjury risk [7, 101, 111, 155].

A possibly overlooked factor in ACL injury prevention and rehabilitation design is visual-motor control associated with maintaining neuromuscular joint-to-joint integrity while engaging in the complex athletic environment [35, 237]. As physical activity and athletic participation require high demand on the visual-motor system to maintain environmental interaction as well as neuromuscular integrity, visual disruption in rehabilitation may be a promising tool to more closely mimic sport demands. The ability to sustain motor control in the variable sport environment demands a complex CNS integration of a constantly changing profile of sensory inputs including visual feedback, proprioception, and vestibular equilibrium to maintain neuromuscular control [87, 88].

The increased visual-motor activation in those with ACL injury suggests an adapted motor control strategy that may not be rectified with current rehabilitation methods. Advancing the neuromuscular control challenge during rehabilitation and prevention strategies can facilitate neuroplasticity not only for the motor regions, but also improve sensory integration and, thereby, address the visual processing bias. The key to this training is to consider the focus of attention, task complexity, visual input, and cognitive load during rehabilitation [114, 225]. Many mechanisms are available, including incorporating reaction time components [225], ball tracking, engaging other players [217], adding decision making [114] or anticipatory aspects [225] and having the patient dual task [214] by engaging the upper extremity while doing lower extremity exercises, or simply occupying the mind with memory or related tasks, can all increase the neural demand of our neuromuscular training strategies. Additionally, as eyes closed or blindfolded conditions have a greater effect on balance and movement performance in those with ACL injury, incorporating them during rehabilitation may address the visual-motor neuroplasticity [82, 108]. New technologies such as stroboscopic glasses provide a means to directly perturbate the visual-motor system under a variety of novel conditions that may help the transition back to the athletic environment, where visual attention is constantly distracted [238, 239]. Previous research using vision obstruction (blindfold) demonstrates alterations in landing neuromuscular control that may increase injury risk [240, 241]. Due to the method of limiting vision, these investigations lacked generalizability and sport specificity as the tasks were simple single movements without environmental interaction. The development of stroboscopic glasses that disrupt vision, without completely removing it, now allows visual-motor assessment during dynamic movements and target acquisition tasks. Stroboscopic glasses technology allows the patient to engage in neuromuscular training under depressed visual feedback and increased cognitive load in a safe clinical environment. This ability to train under a visually disrupted or knockdown stress may provide a means to target unique neuroplastic factors in rehabilitation [242, 243]. The consideration of visual-motor approaches during injury prevention and rehabilitation programs may provide a means to further improve intervention effectiveness. These approaches can be paired with foundational neuromuscular techniques for optimizing strength, multiplanar knee and trunk control, and movement asymmetries [244]. The use of a direct visual disruption technology such as stroboscopic glasses provides an opportunity to supplement traditional interventions [214, 242]. The clinician can add another training area that may decrease injury risk by targeting visual-motor processing along with the traditional neuromuscular, strength, and movement dysfunctions [170, 245]. The cognitive approximation of the demands involved in higher intensity athletic activity under the supervision of a well-trained clinician may further decrease musculoskeletal injury risk. Recognition of the visual-motor implications for maintaining neuromuscular control and injury avoidance may help to mitigate injury risk.

While the suggestions above provide a direct method to challenge the visual-motor system during high level dynamic movements, training the visual processing system in isolation may also have a beneficial effect on neuromuscular control. Swanik et al. provided prospective evidence for decreased visual processing speed as a risk factor for primary ACL injury [127]. Swanik et al. [127] prospectively reported that decreased aspects of neurocognitive function increased the risk of experiencing a noncontact ACL injury. Specifically, reaction time, visual processing, and memory, measured via a computerized concussion baseline assessment (IMPACT), were significantly lower than matched controls [127]. The role of visual-motor function and reaction time to facilitate preparation of the neuromuscular system in anticipation of high-risk situations, maneuvers, or incoming players, provides the theorized mechanism for neurocognition to influence musculoskeletal injury risk [246, 247]. Faster reaction time or processing speed may increase the potential to prepare for incoming perturbations or cognitively manage the complex athletic environment, while maintaining neuromuscular control. Visual training has been shown to improve reaction time and visual processing ability related to sport performance and may be worth considering as an aspect of neuromuscular reeducation [238].

If visual-motor processing ability is suboptimal, this may decrease the ability to compensate for external stimuli and/or attenuate the rapid and sometimes unanticipated maneuvers that depend on quick visual-motor interaction [222, 226, 248]. Visual-motor processing is imperative to successful sport function, whereby complex sensory and visual feedback must be handled with minimal preparation time [35, 246]. Visual memory ability may also assist in motor planning during activity as the constantly changing environment (player or ball positions) must be kept in short-term visual memory when planning movement sequences [243]. While limited connections exist relating biomechanical, visual-motor function, and changes induced by ACL injury, previous reports indicate altered neuromuscular control during visual-motor environmental interaction that may influence injury risk mechanics in healthy active participants [114, 219, 221, 226, 227].

16.8 Use of Neuromechanical Principles in Clinical Settings

Traditionally, ACL rehabilitation has focused on remediation of peripheral biomechanical impairments such as ligament laxity, restricted joint motion, and muscle weakness through techniques involving strength, flexibility, balance, and plyometric training in order to return athletes to competition after injury and reduce risk of ACL reinjury [249]. Utilization of neurocognitive training techniques is less common and presents unique challenges to the clinician and/or coach. Not only do athletes present with high variability in physical ability, especially in youth sports, but neurocognitive ability may vary even among athletes with similar physical attributes. In addition, many of the published studies to date using the computerized systems noted previously are potentially cost prohibitive and may be unavailable to most athletes with ACL injuries. Even if such resources are available, the volume of practice likely required to develop neurocognitive skills may compete with already busy training schedules. Finally, tailoring training programs to the unique abilities of the individual athlete as opposed to mass application of neuromuscular programs may hinder large-scale implementation of such strategies. Nonetheless, the massing body of evidence linking neurocognitive function to injury rink cannot be ignored and clinicians must consider all variables when developing programs intended to reduce risk of ACL injury or reinjury.

When implementing neurocognitive training alongside traditional training techniques, care must be taken to monitor task complexity as to not compromise performance. It is well documented that as cognitive demands increase physical performance will decrease [250, 251]. Prior to placing challenging neurocognitive demands on an athlete, a baseline musculoskeletal profile must be established, taking into consideration the athlete's age, skill level, sport, and position. A youth athlete without a basic understanding of body mechanics and movement strategies cannot be expected to maintain the desired knee position while undergoing a high degree of cognitive load. It is therefore advisable that adequate neuromuscular control be achieved prior to progressing cognitive demands. In addition, inexperienced athletes may also perform more poorly in neurocognitive tasks [252] and may have varying ability to process neurocognitive demands, especially if out of context with their sport.

As athletes develop motor skill and move from the cognitive to associative and autonomous stages of motor learning, the training environment should transition from achieving desired performance to facilitating long-term motor learning. As such, the amount and type of feedback should be systematically reduced while simultaneously increasing the complexity of the task environment. One such strategy involves adding cognitive challenges to be performed in conjunction with the physical task (Table 16.2). Often used cognitive tasks include serial sevens, serial threes, spelling words backwards, controlled word association (COWA), and the Stroop task. While these tasks are not specific to sports, they are commonly used to assess an individual's concentration and memory and serve to simulate the volume of information that must be processed during athletic competition.

In addition to cognitive load, an athlete's ability to respond to stimuli may be influenced by their ability to visualize their environment and detect moving targets. In the context of ACL injury, the athlete's ability to react to varying visual or auditory stimuli and then execute the desired motor pattern at high speeds is vitally important. In a training or rehabilitation setting, simple oculomotor exercises may be implemented to ensure

Table 16.2 Cognitive tasks

Serial 3's/7's	Participant asked to perform mental arithmetic, counting backwards from a predetermined number by increments of 3 or 7	Working memory/ attention and mental concentration
Phonemic and semantic word generation (i.e., Controlled Oral Word Association Test/COWAT)	Participant asked to spontaneously produce words belonging to the same category or beginning with the same letter	Executive function (initiation, strategy use, set maintenance, flexibility)
Stroop color and word task	Participant visually presented with a series of words naming different colors, each word is printed in either the color represented or a different color ink (e.g., the word "red" but in blue ink). The participant is asked to name the color of the ink, ignoring the meaning of the word	Selective attention/ inhibition
Digits backwards	Participants are orally provided a string of random numbers which they are asked to repeat in reverse order. The string becomes increasingly longer, provided correct responses given. Working memory/ attention	Working memory/ attention

precise visual skills. The most common trained movements are pursuits, saccades, and convergence. In a subset of individuals, oculomotor impairments have been linked to deficits in neurocognitive scores [253]. Oculomotor training progressions may include self-paced saccades, Hart Charts, pencil push-ups, and Brock strings (Table 16.3). In addition to oculomotor tasks, one cannot neglect the degree of head movement that occurs in sport, as such vestibular training may be of added benefit. Head velocities of up to 6000 deg/s have been detected in running, with an error as small as one degree resulting in visual distortion thus impairing an athlete's ability to detect stimuli [254]. Vestibular training techniques include balance training and adaption exercises, termed vestibular ocular reflex (VOR) exercises. The effectiveness of such exercises has been well documented in individuals with inner ear pathology [255]; however, the effect on athletic performance has not yet been established. Both oculomotor and vestibular exercises may be progressed by manipulating the environment from simple to busy and transitioning targets from predictable/stationary to unpredictable/moving. Coaches and clinicians may use simple hand gestures, cue cards, computer programs, or actual sports equipment/balls as visual targets. As athletes master each task, additional physical demands should be placed on the athlete to simulate the demands of their sport.

Table 16.3 Vision exercises

Saccades	Self-paced saccades	Participant looks back and forth between two targets as quickly as possible
	Hart chart	Participant reads a series of numbers, letters, or symptoms presented in columns. May be read horizontally or vertically in a variety of different patterns
Convergence	Pencil pushups	Participant holds a target (i.e., pencil) in front of your face at a comfortable distance, then moves the target towards their nose focusing on the target with both eyes until they can no longer maintain single binocular vision. The target is then slowly moved away from the participant and the movement is repeated
	Brock strings	Multiple beads are placed on a string. One end of the string is held at the participants nose, the other is fixed some distance away (distance may vary 1–3 m). Participate is asked to focus on the first bead, then the second, and so on until they reach the last bead, at which point the process is repeated in reverse order
Pursuits	Smooth pursuits	May involve tracking any moving object at speeds slow enough as to not elicit saccades

One criticism of sports vision training is a potential lack of transfer to performance on the field. It is therefore essential, in current context, that visual and cognitive training be made to replicate the unique demands of the sport and position. For example, a soccer goalie will require a high degree of hand-eye coordination, but may not need the ball-handling skills of a mid-fielder. In contrast, all positions in basketball require some degree of hand-eye coordination in addition to lower body quickness and agility. It would not be expected for the soccer midfielder to perform at the same level as the goalie in an object detection and interception task, but the midfielder may exhibit a higher degree of lower extremity control in the presence of cognitive loads.

Table 16.4 represents a sample progression of basic movements often used in athletic training routines. The base movement is first made more difficult by the addition of a single visual or cognitive task, and then by the combination of visual and cognitive tasks (Fig. 16.1). If the athlete can accomplish the movement within the desired parameters, the movement may be progressed; in our example, a squat is progressed to depth jump and the sequence is repeated. The exercise continues progressing towards more sports-specific movements to include directional jumping, responding to a variety of cues. Ideally, these movements are progressed to on-field practice with actual opponents as visual cues.

Table 16.4 Example exercise progression (simple → complex)

Squat	Squat + ball catch **OR** serial 3's	Squat + ball catch AND serial 3's	Depth jump	Depth Jump + serial 3's	Depth jump + Simple RT (jump right or left after landing)	Depth jump + Choice RT (jump right if red card, left if black card)
Agility	Lateral shuffle + Ball catch **or** COWAT	Lateral shuffle + Ball catch **and** COWAT	Multi-directional agility (i.e., 4 cone/square drill[a] with predetermined directions	Square drill[a] + COWAT	Square drill[a] + Simple RT (coach points to cone)	Square drill[a] + Choice RT (jump right if red card, left if black card)

Serial 3's, see Table 16.2
COWAT controlled oral word association test, *RT* reaction time
[a]Square drill: see Fig. 16.1

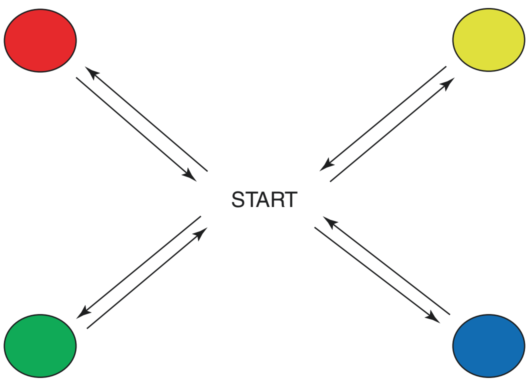


Fig. 16.1 Square drill. Colored flash cards may be used to indicate the target to the patient. A monitor may also be used to display colors via a program such as Microsoft Powerpoint at regular intervals, with the interval increased or decreased depending on the patient's abilities

16.9 Case Examples

16.9.1 Case 1

A 22-year-old female presented status-post ACL repair from an injury occurring during intramural soccer, and with a history of contralateral ACL repair 4 years previously. The patient reported that her rehabilitation and RTS progression after her first surgery only included predictable motor demands and that she never fully regained confidence in her ability to protect herself from future injury, even during simple running tasks. Despite this, she returned to soccer, only to tear her contralateral ACL. For her current injury, the patient progressed as expected through initial phases of the rehabilitation protocol. The addition of cognitive tasks was used to further challenge automaticity of the skills being developed. After exhibiting sufficient strength and balance, agility drills were implemented with progression to unanticipated direction changes utilizing a flanker and Stroop task to challenge concentration. After completing rehabilitation for her second ACL reconstruction, the patient stated her confidence was significantly higher and she planned to continue to include the cognitive demands in her training routine.

16.9.2 Case 2

A 12-year-old female was referred to physical therapy for patellofemoral pain syndrome, with worsening of her injury that occurred during a vault performed during gymnastics practice. Upon initial evaluation, the patient was determined to have inadequate neuromuscular control to maintain a neutral patellofemoral during simple squatting tasks. After 4 weeks of physical therapy, the patient demonstrated the ability to perform depth jumps intended to simulate landing from various heights while maintaining patellofemoral neutral and without pain. However, when a cognitive task (word association) was added to the landing task, the patient immediately reverted to her pre-training movement pattern. The patient was seen for three more weeks with a focus placed on dual task training, specifically during landing tasks. Upon discharge, the patient demonstrated the ability to land with the desired patellofemoral position while attending to various cognitive tasks.

References

1. Gottlob CA, Baker CL Jr. Anterior cruciate ligament reconstruction: socioeconomic issues and cost effectiveness. Am J Orthop. 2000;29(6):472–6.
2. Gottlob CA, Baker CL Jr, Pellissier JM, Colvin L. Cost effectiveness of anterior cruciate ligament reconstruction in young adults. Clin Orthop Relat Res. 1999;367:272-282.
3. Spindler KP, Wright RW. Clinical practice. Anterior cruciate ligament tear. N Engl J Med. 2008;359(20):2135–42.
4. Grindstaff TL, Hammill RR, Tuzson AE, Hertel J. Neuromuscular control training programs and noncontact anterior cruciate ligament injury rates in female athletes: a numbers-needed-to-treat analysis. J Athl Train. 2006;41(4):450–6.
5. Yoo JH, Lim BO, Ha M, et al. A meta-analysis of the effect of neuromuscular training on the prevention of the anterior cruciate ligament injury in female athletes. Knee Surg Sports Traumatol Arthrosc. 2010;18(6):824–30.
6. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. Clin J Sport Med. 2012;22(2):116–21.
7. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. Am J Sports Med. 2010;38(10):1968–78.
8. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. Arthroscopy. 2005;21(8):948–57.
9. Reinecke K, Cordes M, Lerch C, et al. From lab to field conditions: a pilot study on EEG methodology in applied sports sciences. Appl Psychophysiol Biofeedback. 2011;36(4):265–71.
10. DiStefano LJ, Blackburn JT, Marshall SW, Guskiewicz KM, Garrett WE, Padua DA. Effects of an age-specific anterior cruciate ligament injury prevention program on lower extremity biomechanics in children. Am J Sports Med. 2011;39(5):949–57.
11. Heidt RS Jr, Sweeterman LM, Carlonas RL, Traub JA, Tekulve FX. Avoidance of soccer injuries with preseason conditioning. Am J Sports Med. 2000;28(5):659–62.
12. Herman DC, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B, Padua DA. The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. Am J Sports Med. 2008;36(4):733–40.
13. Hewett TE, Ford KR, Hoogenboom BJ, Myer GD. Understanding and preventing ACL injuries: current biomechanical and epidemiologic considerations - update 2010. NAJSPT. 2010;5(4):234–51.
14. Steffen K, Myklebust G, Olsen OE, Holme I, Bahr R. Preventing injuries in female youth footballDOUBLEHYPHENa cluster-randomized controlled trial. Scand J Med Sci Sports. 2008;18(5):605–14.
15. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. J Strength Cond Res. 2005;19(1):51–60.
16. Myer GD, Paterno MV, Ford KR, Hewett TE. Neuromuscular training techniques to target deficits before return to sport after anterior cruciate ligament reconstruction. J Strength Cond Res. 2008;22(3):987–1014.
17. Goerger BM, Marshall SW, Beutler AI, Blackburn JT, Wilckens JH, Padua DA. ACL injury alters pre-injury coordination of the hip and knee: the JUMP ACL study. Med Sci Sports Exerc. 2013;45(5):221.
18. McLean SG. The ACL injury enigma: we can't prevent what we don't understand. J Athl Train. 2008;43(5):538–40.
19. Baumeister J, Reinecke K, Schubert M, Weiss M. Altered electrocortical brain activity after ACL reconstruction during force control. J Orthop Res. 2011;29(9):1383–9.
20. Baumeister J. What the brain can tell us in musculoskeletal rehabilitation. J Sports Med Doping Stud. 2012;2(3):1–2.
21. Beck S, Taube W, Gruber M, Amtage F, Gollhofer A, Schubert M. Task-specific changes in motor evoked potentials of lower limb muscles after different training interventions. Brain Res. 2007;1179:51–60.
22. Benjaminse A, Otten E. ACL injury prevention, more effective with a different way of motor learning? Knee Surg Sports Traumatol Arthrosc. 2011;19(4):622–7.
23. Berthoz A, Lacour M, Soechting J, Vidal P. The role of vision in the control of posture during linear motion. Prog Brain Res. 1979;50:197–209.
24. Valeriani M, Restuccia D, Di Lazzaro V, Franceschi F, Fabbriciani C, Tonali P. Clinical and neurophysiological abnormalities before and after reconstruction of the anterior cruciate ligament of the knee. Acta Neurol Scand. 1999;99(5):303–7.
25. Baumeister J, Reinecke K, Liesen H, Weiss M. Cortical activity of skilled performance in a complex sports related motor task. Eur J Appl Physiol. 2008;104(4):625–31.
26. Hall KG, Magill RA. Variability of practice and contextual interference in motor skill learning. J Mot Behav. 1995;27(4):299–309.

27. Kirkendall DT, Garrett WE Jr. The anterior cruciate ligament enigma. Injury mechanisms and prevention. Clin Orthop Relat Res. 2000;372:64–8.
28. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am J Sports Med. 2004;32(4):1002–12.
29. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. J Am Acad Orthop Surg. 2000;8(3):141–50.
30. McNair PJ, Marshall RN, Matheson JA. Important features associated with acute anterior cruciate ligament injury. N Z Med J. 1990;103(901):537–9.
31. Shimokochi Y, Shultz SJ. Mechanisms of noncontact anterior cruciate ligament injury. J Athl Train. 2008;43(4):396–408.
32. Boden BP, Torg JS, Knowles SB, Hewett TE. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. Am J Sports Med. 2009;37(2):252–9.
33. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. Br J Sports Med. 2009;43(6):417–22.
34. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. Am J Sports Med. 2010;38(11):2218–25.
35. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball - video analysis of 39 cases. Am J Sports Med. 2007;35(3):359–67.
36. Hewett TE, Zazulak BT, Myer GD. Effects of the menstrual cycle on anterior cruciate ligament injury risk: a systematic review. Am J Sports Med. 2007;35(4):659–68.
37. Ruedl G, Ploner P, Linortner I, et al. Are oral contraceptive use and menstrual cycle phase related to anterior cruciate ligament injury risk in female recreational skiers? Knee Surg Sports Traumatol Arthrosc. 2009;17(9):1065–9.
38. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. J Athl Train. 2007;42(2):311–9.
39. Majewski M, Susanne H, Klaus S. Epidemiology of athletic knee injuries: a 10-year study. Knee. 2006;13(3):184–8.
40. Chaudhari AM, Zelman EA, Flanigan DC, Kaeding CC, Nagaraja HN. Anterior cruciate ligament-injured subjects have smaller anterior cruciate ligaments than matched controls: a magnetic resonance imaging study. Am J Sports Med. 2009;37(7):1282–7.
41. Everhart JS, Flanigan DC, Simon RA, Chaudhari AM. Association of noncontact anterior cruciate ligament injury with presence and thickness of a bony ridge on the anteromedial aspect of the femoral intercondylar notch. Am J Sports Med. 2010;38(8):1667–73.
42. Jamison ST, Flanigan DC, Nagaraja HN, Chaudhari AM. Side-to-side differences in anterior cruciate ligament volume in healthy control subjects. J Biomech. 2010;43(3):576–8.
43. Simon RA, Everhart JS, Nagaraja HN, Chaudhari AM. A case-control study of anterior cruciate ligament volume, tibial plateau slopes and intercondylar notch dimensions in ACL-injured knees. J Biomech. 2010;43(9):1702–7.
44. Hewett TE, Lynch TR, Myer GD, Ford KR, Gwin RC, Heidt RS Jr. Multiple risk factors related to familial predisposition to anterior cruciate ligament injury: fraternal twin sisters with anterior cruciate ligament ruptures. Br J Sports Med. 2010;44(12):848–55.
45. Posthumus M, Collins M, van der Merwe L, et al. Matrix metalloproteinase genes on chromosome 11q22 and the risk of anterior cruciate ligament (ACL) rupture. Scand J Med Sci Sports. 2012;22(4):523–33.
46. Raleigh SM, Posthumus M, O'Cuinneagain D, van der Merwe W, Collins M. The GDF5 gene and anterior cruciate ligament rupture. Int J Sports Med. 2013;34(4):364–7.
47. Greska EK, Cortes N, Van Lunen BL, Onate JA. A feedback inclusive neuromuscular training program alters frontal plane kinematics. J Strength Cond Res. 2011;26(6):1609–19.
48. McCann R, Nelson C, Van Lunen B, Greska E, Ringleb S, Onate J. Neuromuscular changes following an injury prevention program for ACL injuries. Int J Athl Ther Train. 2011;14(4):16–20.
49. Noyes FR, Barber-Westin SD, Smith ST, Campbell T. A training program to improve neuromuscular indices in female high school volleyball players. J Strength Cond Res. 2011;25(8):2151–60.
50. Pollard CD, Sigward SM, Powers CM. Injury prevention training results in biomechanical changes consistent with decreased knee loading in female athletes during landing. Knee. 2009;4:5.
51. Zemkova E, Hamar D. The effect of 6-week combined agility-balance training on neuromuscular performance in basketball players. J Sports Med Phys Fitness. 2010;50(3):262–7.
52. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med. 2005;33(4):492–501.
53. Myer GD, Ford KR, Barber Foss KD, Liu C, Nick TG, Hewett TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. Clin J Sport Med. 2009;19(1):3–8.
54. Padua DAMS, Beutler AI, Garrett WE. Prospective cohort study of biomechanical risk factors of ACL injury: The JUMP-ACL Study. American Orthopaedic Society of Sports Medicine Annual Meeting; 2009; Keystone.
55. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of

the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. Am J Sports Med. 2007;35(7):1123–30.
56. Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among female athletes: a systematic review of neuromuscular training interventions. J Knee Surg. 2005;18(1):82–8.
57. Doyon J, Benali H. Reorganization and plasticity in the adult brain during learning of motor skills. Curr Opin Neurobiol. 2005;15(2):161–7.
58. Grooms DR, Kiefer AW, Riley MA, et al. Brain-behavior mechanisms for the transfer of neuromuscular training adaptions to simulated sport: initial findings from the train the brain project. J Sport Rehabil. 2018;27(5):1–5. https://doi.org/10.1123/jsr.2017-0241.
59. Jensen JL, Marstrand PC, Nielsen JB. Motor skill training and strength training are associated with different plastic changes in the central nervous system. J Appl Physiol. 2005;99(4):1558–68.
60. Muellbacher W, Ziemann U, Boroojerdi B, Cohen L, Hallett M. Role of the human motor cortex in rapid motor learning. Exp Brain Res. 2001;136(4):431–8.
61. Powers CM, Fisher B. Mechanisms underlying ACL injury-prevention training: the brain-behavior relationship. J Athl Train. 2010;45(5):513–5.
62. Schubert M, Beck S, Taube W, Amtage F, Faist M, Gruber M. Balance training and ballistic strength training are associated with task-specific corticospinal adaptations. Eur J Neurosci. 2008;27(8):2007–18.
63. Ungerleider LG, Doyon J, Karni A. Imaging brain plasticity during motor skill learning. Neurobiol Learn Mem. 2002;78(3):553–64.
64. Gokeler A, Benjaminse A, Hewett TE, et al. Feedback techniques to target functional deficits following anterior cruciate ligament reconstruction: implications for motor control and reduction of second injury risk. Sports Med. 2013;43(11):1065–74.
65. Onate JA, Guskiewicz KM, Marshall SW, Giuliani C, Yu B, Garrett WE. Instruction of jump-landing technique using videotape feedback: altering lower extremity motion patterns. Am J Sports Med. 2005;33(6):831–42.
66. Padua DA, DiStefano LJ, Marshall SW, Beutler AI, de la Motte SJ, DiStefano MJ. Retention of movement pattern changes after a lower extremity injury prevention program is affected by program duration. Am J Sports Med. 2012;40(2):300–6.
67. Emanuel M, Jarus T, Bart O. Effect of focus of attention and age on motor acquisition, retention, and transfer: a randomized trial. Phys Ther. 2008;88(2):251–60.
68. Herman DC, Onate JA, Weinhold PS, et al. The effects of feedback with and without strength training on lower extremity biomechanics. Am J Sports Med. 2009;37(7):1301–8.
69. Onate JA, Guskiewicz KM, Sullivan RJ. Augmented feedback reduces jump landing forces. J Orthop Sports Phys Ther. 2001;31(9):511–7.
70. Seidler RD, Noll DC. Neuroanatomical correlates of motor acquisition and motor transfer. J Neurophysiol. 2008;99(4):1836–45.
71. Wood CA, Ging CA. The role of interference and task similarity on the acquisition, retention, and transfer of simple motor skills. Res Q Exerc Sport. 1991;62(1):18–26.
72. Grandstrand SL, Pfeiffer RP, Sabick MB, DeBeliso M, Shea KG. The effects of a commercially available warm-up program on landing mechanics in female youth soccer players. J Strength Cond Res. 2006;20(2):331–5.
73. Pfeiffer RP, Shea KG, Roberts D, Grandstrand S, Bond L. Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. J Bone Joint Surg. 2006;88(8):1769–74.
74. Soderman K, Werner S, Pietila T, Engstrom B, Alfredson H. Balance board training: prevention of traumatic injuries of the lower extremities in female soccer players? A prospective randomized intervention study. Knee Surg Sports Traumatol Arthrosc. 2000;8(6):356–63.
75. Gardinier ES, Di Stasi S, Manal K, Buchanan TS, Snyder-Mackler L. Knee contact force asymmetries in patients who failed return-to-sport readiness criteria 6 months after anterior cruciate ligament reconstruction. Am J Sports Med. 2014;42(12):2917–25.
76. Larsen JB, Farup J, Lind M, Dalgas U. Muscle strength and functional performance is markedly impaired at the recommended time point for sport return after anterior cruciate ligament reconstruction in recreational athletes. Hum Mov Sci. 2015;39:73–87.
77. Logerstedt D, Di Stasi S, Grindem H, et al. Self-reported knee function can identify athletes who fail return-to-activity criteria up to 1 year after anterior cruciate ligament reconstruction: a delaware-oslo ACL cohort study. J Orthop Sports Phys Ther. 2014;44(12):914–23.
78. Knoll Z, Kiss RM, Kocsis L. Gait adaptation in ACL deficient patients before and after anterior cruciate ligament reconstruction surgery. J Electromyogr Kinesiol. 2004;14(3):287–94.
79. Myer GD, Martin L Jr, Ford KR, et al. No association of time from surgery with functional deficits in athletes after anterior cruciate ligament reconstruction: evidence for objective return-to-sport criteria. Am J Sports Med. 2012;40(10):2256–63.
80. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. Clin J Sport Med. 2007;17(4):258–62.
81. Ageberg E, Friden T. Normalized motor function but impaired sensory function after unilateral non-reconstructed ACL injury: patients compared with uninjured controls. Knee Surg Sports Traumatol Arthrosc. 2008;16(5):449–56.
82. Friden T, Roberts D, Movin T, Wredmark T. Function after anterior cruciate ligament injuries - influence of visual control and proprioception. Acta Orthop Scand. 1998;69(6):590–4.
83. Roberts D, Ageberg E, Andersson G, Friden T. Clinical measurements of proprioception, muscle

strength and laxity in relation to function in the ACL-injured knee. Knee Surg Sports Traumatol Arthrosc. 2007;15(1):9–16.
84. Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. Clin Sports Med. 2008;27(3):353–70.
85. Kandel ER, Schwartz JH, Jessell TM. Principles of neural science, vol. 4. New York: McGraw-Hill; 2000.
86. Lederman E. The fall of the postural-structural-biomechanical model in manual and physical therapies: exemplified by lower back pain. J Bodyw Mov Ther. 2011;15(2):131–8.
87. Magill RA. Motor learning and control: concepts and applications, vol. 11. New York: McGraw-Hill; 2007.
88. Winter DA. Biomechanics and motor control of human movement. Waterloo: Wiley; 2009.
89. Gomez-Barrena E, Martinez-Moreno E, Munuera L. Segmental sensory innervation of the anterior cruciate ligament and the patellar tendon of the cat's knee. Acta Orthop Scand. 1996;67(6):545–52.
90. Gomez-Barrena E, Nunez A, Martinez-Moreno E, Valls J, Munuera L. Neural and muscular electric activity in the cat's knee. Changes when the anterior cruciate ligament is transected. Acta Orthop Scand. 1997;68(2):149–55.
91. Park HB, Koh M, Cho SH, Hutchinson B, Lee B. Mapping the rat somatosensory pathway from the anterior cruciate ligament nerve endings to the cerebrum. J Orthop Res. 2005;23(6):1419–24.
92. Adachi N, Ochi M, Uchio Y, Iwasa J, Ryoke K, Kuriwaka M. Mechanoreceptors in the anterior cruciate ligament contribute to the joint position sense. Acta Orthop. 2002;73(3):330–4.
93. Fremerey RW, Lobenhoffer P, Zeichen J, Skutek M, Bosch U, Tscherne H. Proprioception after rehabilitation and reconstruction in knees with deficiency of the anterior cruciate ligament: a prospective, longitudinal study. J Bone Joint Surg. 2000;82(6):801–6.
94. Kennedy JC, Alexander IJ, Hayes KC. Nerve supply of the human knee and its functional importance. Am J Sports Med. 1982;10(6):329–35.
95. Schutte MJ, Dabezies EJ, Zimny ML, Happel LT. Neural anatomy of the human anterior cruciate ligament. J Bone Joint Surg. 1987;69(2):243–7.
96. Zimny ML, Schutte M, Dabezies E. Mechanoreceptors in the human anterior cruciate ligament. Anat Rec. 1986;214(2):204–9.
97. Santello M, McDonagh MJN, Challis JH. Visual and non-visual control of landing movements in humans. J Physiol. 2001;537(1):313–27.
98. Scheidt RA, Conditt MA, Secco EL, Mussa-Ivaldi FA. Interaction of visual and proprioceptive feedback during adaptation of human reaching movements. J Neurophysiol. 2005;93(6):3200–13.
99. Thompson HW, McKinley PA. Landing from a jump: the role of vision when landing from known and unknown heights. Neuroreport. 1995;6(3):581–4.
100. Wade MG, Jones G. The role of vision and spatial orientation in the maintenance of posture. Phys Ther. 1997;77(6):619–28.
101. Baumeister J, Reinecke K, Weiss M. Changed cortical activity after anterior cruciate ligament reconstruction in a joint position paradigm: an EEG study. Scand J Med Sci Sports. 2008;18(4):473–84.
102. Courtney C, Rine RM, Kroll P. Central somatosensory changes and altered muscle synergies in subjects with anterior cruciate ligament deficiency. Gait Posture. 2005;22(1):69–74.
103. Courtney CA, Rine RM. Central somatosensory changes associated with improved dynamic balance in subjects with anterior cruciate ligament deficiency. Gait Posture. 2006;24(2):190–5.
104. Ergen E, Ulkar B. Proprioception and ankle injuries in soccer. Clin Sports Med. 2008;27(1):195–217.
105. Hopper DM, Creagh MJ, Formby PA, Goh SC, Boyle JJ, Strauss GR. Functional measurement of knee joint position sense after anterior cruciate ligament reconstruction. Arch Phys Med Rehabil. 2003;84(6):868–72.
106. Hopper DM, Strauss GR, Boyle JJ, Bell J. Functional recovery after anterior cruciate ligament reconstruction: a longitudinal perspective. Arch Phys Med Rehabil. 2008;89(8):1535–41.
107. Kapreli E, Athanasopoulos S, Gliatis J, et al. Anterior cruciate ligament deficiency causes brain plasticity: a functional MRI study. Am J Sports Med. 2009;37(12):2419–26.
108. Okuda K, Abe N, Katayama Y, Senda M, Kuroda T, Inoue H. Effect of vision on postural sway in anterior cruciate ligament injured knees. J Orthop Sci. 2005;10(3):277–83.
109. Peuskens H, Vanrie J, Verfaillie K, Orban G. Specificity of regions processing biological motion. Eur J Neurosci. 2005;21(10):2864–75.
110. Konishi YU. ACL repair might induce further abnormality of gamma loop in the intact side of the quadriceps femoris. Int J Sports Med. 2011;32(4):292–6.
111. Madhavan S, Shields RK. Neuromuscular responses in individuals with anterior cruciate ligament repair. Clin Neurophysiol. 2011;122(5):997–1004.
112. Araújo D, Hristovski R, Seifert L, et al. Ecological cognition: expert decision-making behaviour in sport. Int Rev Sport Exerc Psychol. 2017;15:1–25.
113. Barrett LF, Simmons WK. Interoceptive predictions in the brain. Nat Rev Neurosci. 2015;16(7):419–29.
114. Borotikar BS, Newcomer R, Koppes R, McLean SG. Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. Clin Biomech. 2008;23(1):81–92.
115. Farrow D, Abernethy B. Do expertise and the degree of perception—action coupling affect natural anticipatory performance? Perception. 2003;32(9):1127–39.
116. Hadlow SMPD, Mann DL, Portus MR, Abernethy B. Modified perceptual training in sport: a new classification framework. J Sci Med Sport. 2018;21(9):950–8.

117. Needle AR, Lepley AS, Grooms DR. Central nervous system adaptation after ligamentous injury: a summary of theories, evidence, and clinical interpretation. Sports Med. 2017;47(7):1271–88.
118. Wilkerson GB, Grooms DR, Acocello SN. Neuromechanical considerations for postconcussion musculoskeletal injury risk management. Curr Sports Med Rep. 2017;16(6):419–27.
119. Wahn B, König P. Is attentional resource allocation across sensory modalities task-dependent? Adv Cogn Psychol. 2017;13(1):83–96.
120. Kastner S, Ungerleider LG. Mechanisms of visual attention in the human cortex. Annu Rev Neurosci. 2000;23(1):315–41.
121. Pisella L. Visual perception is dependent on visuospatial working memory and thus on the posterior parietal cortex. Ann Phys Rehabil Med. 2017;60(3):141–7.
122. Wolpert DM, Diedrichsen J, Flanagan JR. Principles of sensorimotor learning. Nat Rev Neurosci. 2011;12(12):739–51.
123. Pessoa L, Kastner S, Ungerleider LG. Neuroimaging studies of attention: from modulation of sensory processing to top-down control. J Neurosci. 2003;23(10):3990–8.
124. Puglisi G, Leonetti A, Landau A, et al. The role of attention in human motor resonance. PLoS ONE. 2017;12(5):e0177457.
125. Taimela S, Kujala UM, Osterman K. The relation of low grade mental ability to fractures in young men. Int Orthop. 1991;15:75–7.
126. Taimela S, Osterman L, Kujala U, et al. Motor ability and personality with reference to soccer injuries. J Sports Med Phys Fitness. 1990;30:194–201.
127. Swanik CB, Covassin T, Stearne DJ, Schatz P. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. Am J Sports Med. 2007;35(6):943–8.
128. Dai B, Cook RF, Meyer EA, Sciascia Y, Hinshaw TJ, Wang C, Zhu Q. The effect of a secondary cognitive task on landing mechanics and jump performance. Sports Biomech. 2018 Jun;17(2):192–205.
129. Kim AS, Needle AR, Thomas SJ, Higginson CI, Kaminski TW, Swanik CB. A sex comparison of reactive knee stiffness regulation strategies under cognitive loads. Clin Biomech. 2016;35:86–92.
130. Herman DC, Barth JT. Drop-jump landing varies with baseline neurocognition: implications for anterior cruciate ligament injury risk and prevention. Am J Sports Med. 2016;44(9):2347–53.
131. McLean SG, Borotikar B, Lucey SM. Lower limb muscle pre-motor time measures during a choice reaction task associate with knee abduction loads during dynamic single leg landings. Clin Biomech. 2010;25(6):563–9.
132. An YW, DiTrani Lobacz A, Lehmann T, et al. Neuroplastic changes in ACLR patients from neuromechanical decoupling. Scand J Med Sci Sports. 2018;29:251–8. https://doi.org/10.1111/sms.13322.
133. Valeriani M, Restuccia D, Di Lazzaro V, Franceschi F, Fabbriciani C, Tonali P. Central nervous system modifications in patients with lesion of the anterior cruciate ligament of the knee. Brain. 1996;119(Pt 5):1751–62.
134. Grooms DR, Page SJ, Nichols-Larsen DS, Chaudhari AM, White SE, Onate JA. Neuroplasticity associated with anterior cruciate ligament reconstruction. J Orthop Sport Phys. 2017;47(3):180–9.
135. Song K, Burcal CJ, Hertel J, Wikstrom EA. Increased visual use in chronic ankle instability: a meta-analysis. Med Sci Sports Exerc. 2016;48(10):2046–56.
136. Grooms D, Appelbaum G, Onate J. Neuroplasticity following anterior cruciate ligament injury: a framework for visual-motor training approaches in rehabilitation. J Orthop Sports Phys Ther. 2015;45(5):381–93.
137. Grooms DR, Page SJ, Onate JA. Brain activation for knee movement measured days before second anterior cruciate ligament injury: neuroimaging in musculoskeletal medicine. J Athl Train. 2015;50(10):1005–10.
138. Churchill N, Hutchison MG, Leung G, et al. Changes in functional connectivity of the brain associated with a history of sport concussion: a preliminary investigation. Brain Inj. 2017;31(1):39–48.
139. Parasuraman R, Jiang Y. Individual differences in cognition, affect, and performance: behavioral, neuroimaging, and molecular genetic approaches. NeuroImage. 2012;59(1):70–82.
140. Serrien DJ, Ivry RB, Swinnen SP. The missing link between action and cognition. Prog Neurobiol. 2007;82(2):95–107.
141. Taubert M, Draganski B, Anwander A, et al. Dynamic properties of human brain structure: learning-related changes in cortical areas and associated fiber connections. J Neurosci. 2010;30(35):11670–7.
142. Wu T, Liu J, Hallett M, et al. Cerebellum and integration of neural networks in dual-task processing. NeuroImage. 2013;65:466–75.
143. Bressler SL, Menon V. Large-scale brain networks in cognition: emerging methods and principles. Trends Cogn Sci. 2010;14(6):277–90.
144. Harris KD, Thiele A. Cortical state and attention. Nat Rev Neurosci. 2012;12(9):509–23.
145. Heinen K, Feredoes E, Ruff CC, et al. Functional connectivity between prefrontal and parietal cortex drives visuo-spatial attention shifts. Neuropsychologia. 2017;99:81–91.
146. Kahn AE, Mattar MG, Vettel JM, et al. Structural pathways supporting swift acquisition of new visuomotor skills. Cereb Cortex. 2017;27(1):173–84.
147. Sridharan D, Levitin DJ, Menon V. A critical role for the right fronto-insular cortex in switching between central-executive and default-mode networks. Proc Nat Acad Sci. 2008;105(34):12569–74.
148. Weissman DH, Roberts K, Visscher K, et al. The neural bases of momentary lapses in attention. Nat Neurosci. 2006;9(7):971.

149. Rémy F, Wenderoth N, Lipkens K, et al. Dual-task interference during initial learning of a new motor task results from competition for the same brain areas. Neuropsychologia. 2010;48(9):2517–27.
150. Shuggi IM, Oh H, Shewokis PA, et al. Mental workload and motor performance dynamics during practice of reaching movements under various levels of task difficulty. Neuroscience. 2017;360:166–79.
151. Nakata H, Yoshie M, Miura A, et al. Characteristics of the athletes' brain: evidence from neurophysiology and neuroimaging. Brain Res Rev. 2010;62(2):197–211.
152. Wilkerson GB, Nabhan DC, Prusmack CJ, et al. Detection of persisting concussion effects on neuromechanical responsiveness. Med Sci Sports Exerc. 2018;50(9):1750–6.
153. Kapreli E, Athanasopoulos S. The anterior cruciate ligament deficiency as a model of brain plasticity. Med Hypotheses. 2006;67(3):645–50.
154. Pitman MI, Nainzadeh N, Menche D, Gasalberti R, Song EK. The intraoperative evaluation of the neurosensory function of the anterior cruciate ligament in humans using somatosensory evoked potentials. Arthroscopy. 1992;8(4):442–7.
155. Brumagne S, Cordo P, Verschueren S. Proprioceptive weighting changes in persons with low back pain and elderly persons during upright standing. Neurosci Lett. 2004;366(1):63–6.
156. Im HJ, Kim JS, Li X, et al. Alteration of sensory neurons and spinal response to an experimental osteoarthritis pain model. Arthritis Rheum. 2010;62(10):2995–3005.
157. Levine JD, Dardick SJ, Basbaum AI, Scipio E. Reflex neurogenic inflammation. I. Contribution of the peripheral nervous system to spatially remote inflammatory responses that follow injury. J Neurosci. 1985;5(5):1380–6.
158. Myer GD, Schmitt LC, Brent JL, et al. Utilization of modified NFL combine testing to identify functional deficits in athletes following ACL reconstruction. J Orthop Sports Phys Ther. 2011;41(6):377–87.
159. Roewer BD, Di Stasi SL, Snyder-Mackler L. Quadriceps strength and weight acceptance strategies continue to improve two years after anterior cruciate ligament reconstruction. J Biomech. 2011;44(10):1948–53.
160. Bates NA, Ford KR, Myer GD, Hewett TE. Impact differences in ground reaction force and center of mass between the first and second landing phases of a drop vertical jump and their implications for injury risk assessment. J Biomech. 2013;46(7):1237–41.
161. Ernst GP, Saliba E, Diduch DR, Hurwitz SR, Ball DW. Lower extremity compensations following anterior cruciate ligament reconstruction. Phys Ther. 2000;80(3):251–60.
162. Courtney CA, Durr RK, Emerson-Kavchak AJ, Witte EO, Santos MJ. Heightened flexor withdrawal responses following ACL rupture are enhanced by passive tibial translation. Clin Neurophysiol. 2011;122(5):1005–10.
163. Konishi Y, Fukubayashi T, Takeshita D. Possible mechanism of quadriceps femoris weakness in patients with ruptured anterior cruciate ligament. Med Sci Sports Exerc. 2002;34(9):1414–8.
164. Konishi Y, Konishi H, Fukubayashi T. Gamma loop dysfunction in quadriceps on the contralateral side in patients with ruptured ACL. Med Sci Sports Exerc. 2003;35(6):897–900.
165. Konishi Y, Aihara Y, Sakai M, Ogawa G, Fukubayashi T. Gamma loop dysfunction in the quadriceps femoris of patients who underwent anterior cruciate ligament reconstruction remains bilaterally. Scand J Med Sci Sports. 2007;17(4):393–9.
166. Di Fabio RP, Graf B, Badke MB, Breunig A, Jensen K. Effect of knee joint laxity on long-loop postural reflexes: evidence for a human capsular-hamstring reflex. Exp Brain Res. 1992;90(1):189–200.
167. Boudreau SA, Farina D, Falla D. The role of motor learning and neuroplasticity in designing rehabilitation approaches for musculoskeletal pain disorders. Man Ther. 2010;15(5):410–4.
168. Knecht S, Henningsen H, Elbert T, et al. Cortical reorganization in human amputees and mislocalization of painful stimuli to the phantom limb. Neurosci Lett. 1995;201(3):262–4.
169. Torquati K, Pizzella V, Babiloni C, et al. Nociceptive and non-nociceptive sub-regions in the human secondary somatosensory cortex: an MEG study using fMRI constraints. NeuroImage. 2005;26(1):48–56.
170. Grooms DR, Chaudhari A, Page SJ, Nichols-Larsen DS, Onate JA. Visual-motor control of drop landing after anterior cruciate ligament reconstruction. J Athl Train. 2018;53(5):486–96.
171. Grooms DR, Page SJ, Nichols-Larsen DS, et al. Neuroplasticity associated with anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2017;47(3):180–9.
172. Biedert R, Zwick E. Ligament-muscle reflex arc after anterior cruciate ligament reconstruction: electromyographic evaluation. Arch Orthop Trauma Surg. 1998;118(1-2):81–4.
173. Konishi Y, Fukubayashi T, Takeshita D. Mechanism of quadriceps femoris muscle weakness in patients with anterior cruciate ligament reconstruction. Scand J Med Sci Sports. 2002;12(6):371–5.
174. Roberts D, Friden T, Stomberg A, Lindstrand A, Moritz U. Bilateral proprioceptive defects in patients with a unilateral anterior cruciate ligament reconstruction: a comparison between patients and healthy individuals. J Orthop Res. 2000;18(4):565–71.
175. Pietrosimone BG, Lepley AS, Ericksen HM, Gribble PA, Levine J. Quadriceps strength and corticospinal excitability as predictors of disability after anterior cruciate ligament reconstruction. J Sport Rehabil. 2013;22(1):1–6.
176. Pietrosimone BG, McLeod MM, Lepley AS. A theoretical framework for understanding neuromuscular response to lower extremity joint injury. Sports Health. 2012;4(1):31–5.

177. Lepley AS, Bahhur NO, Murray AM, Pietrosimone BG. Quadriceps corticomotor excitability following an experimental knee joint effusion. Knee Surg Sports Traumatol Arthrosc. 2013;23(4):1010–7.
178. Lepley AS, Ericksen HM, Sohn DH, Pietrosimone BG. Contributions of neural excitability and voluntary activation to quadriceps muscle strength following anterior cruciate ligament reconstruction. Knee. 2014;21(3):736–42.
179. Bonfim TR, Jansen Paccola CA, Barela JA. Proprioceptive and behavior impairments in individuals with anterior cruciate ligament reconstructed knees. Arch Phys Med Rehabil. 2003;84(8):1217–23.
180. Friden T, Roberts D, Ageberg E, Walden M, Zatterstrom R. Review of knee proprioception and the relation to extremity function after an anterior cruciate ligament rupture. J Orthop Sports Phys Ther. 2001;31(10):567–76.
181. Heroux ME, Tremblay F. Weight discrimination after anterior cruciate ligament injury: a pilot study. Arch Phys Med Rehabil. 2005;86(7):1362–8.
182. Heroux ME, Tremblay F. Corticomotor excitability associated with unilateral knee dysfunction secondary to anterior cruciate ligament injury. Knee Surg Sports Traumatol Arthrosc. 2006;14(9):823–33.
183. Norte GE, Pietrosimone BG, Hart JM, Hertel J, Ingersoll CD. Relationship between transcranial magnetic stimulation and percutaneous electrical stimulation in determining the quadriceps central activation ratio. Am J Phys Med Rehabil. 2010;89(12):986–96.
184. Hamzei F, Liepert J, Dettmers C, Weiller C, Rijntjes M. Two different reorganization patterns after rehabilitative therapy: an exploratory study with fMRI and TMS. NeuroImage. 2006;31(2):710–20.
185. On AY, Uludag B, Taskiran E, Ertekin C. Differential corticomotor control of a muscle adjacent to a painful joint. Neurorehabil Neural Repair. 2004;18(3):127–33.
186. Tinazzi M, Rosso T, Zanette G, Fiaschi A, Aglioti SM. Rapid modulation of cortical proprioceptive activity induced by transient cutaneous deafferentation: neurophysiological evidence of short-term plasticity across different somatosensory modalities in humans. Eur J Neurosci. 2003;18(11): 3053–60.
187. Zanette G, Manganotti P, Fiaschi A, Tamburin S. Modulation of motor cortex excitability after upper limb immobilization. Clin Neurophysiol. 2004;115(6):1264–75.
188. Ball T, Schreiber A, Feige B, Wagner M, Lucking CH, Kristeva-Feige R. The role of higher-order motor areas in voluntary movement as revealed by high-resolution EEG and fMRI. NeuroImage. 1999;10(6):682–94.
189. Nachev P, Wydell H, O'Neill K, Husain M, Kennard C. The role of the pre-supplementary motor area in the control of action. NeuroImage. 2007;36(Suppl 2):T155–63.
190. Meister I, Krings T, Foltys H, et al. Effects of long-term practice and task complexity in musicians and nonmusicians performing simple and complex motor tasks: implications for cortical motor organization. Hum Brain Mapp. 2005;25(3):345–52.
191. Chen TL, Babiloni C, Ferretti A, et al. Human secondary somatosensory cortex is involved in the processing of somatosensory rare stimuli: an fMRI study. NeuroImage. 2008;40(4):1765–71.
192. Ferretti A, Babiloni C, Gratta CD, et al. Functional topography of the secondary somatosensory cortex for nonpainful and painful stimuli: an fMRI study. NeuroImage. 2003;20(3):1625–38.
193. Binder JR, Desai RH. The neurobiology of semantic memory. Trends Cogn Sci. 2011;15(11):527–36.
194. Bonner MF, Price AR. Where is the anterior temporal lobe and what does it do? J Neurosci. 2013;33(10):4213–5.
195. Smith WM, Bowen KF. The effects of delayed and displaced visual feedback on motor control. J Mot Behav. 1980;12(2):91–101.
196. Warren WH Jr, Kay BA, Zosh WD, Duchon AP, Sahuc S. Optic flow is used to control human walking. Nat Neurosci. 2001;4(2):213–6.
197. Amador N, Fried I. Single-neuron activity in the human supplementary motor area underlying preparation for action. J Neurosurg. 2004;100(2):250–9.
198. Dault MC, Frank JS, Allard F. Influence of a visuo-spatial, verbal and central executive working memory task on postural control. Gait Posture. 2001;14(2):110–6.
199. Lajoie Y, Teasdale N, Bard C, Fleury M. Attentional demands for static and dynamic equilibrium. Exp Brain Res. 1993;97(1):139–44.
200. Remaud A, Boyas S, Lajoie Y, Bilodeau M. Attentional focus influences postural control and reaction time performances only during challenging dual-task conditions in healthy young adults. Exp Brain Res. 2013;231(2):219–29.
201. Wulf G. Attentional focus and motor learning: a review of 15 years. Int Rev Sport Exer Psychol. 2013;6(1):77–104.
202. Babiloni C, Marzano N, Infarinato F, et al. "Neural efficiency" of experts' brain during judgment of actions: a high-resolution EEG study in elite and amateur karate athletes. Behav Brain Res. 2010;207(2):466–75.
203. Del Percio C, Babiloni C, Marzano N, et al. "Neural efficiency" of athletes' brain for upright standing: a high-resolution EEG study. Brain Res Bull. 2009;79(3-4):193–200.
204. Ageberg E, Roberts D, Holmstrom E, Friden T. Balance in single-limb stance in patients with anterior cruciate ligament injury: relation to knee laxity, proprioception, muscle strength, and subjective function. Am J Sports Med. 2005;33(10):1527–35.
205. Jarus T, Gutman T. Effects of cognitive processes and task complexity on acquisition, retention, and transfer of motor skills. Can J Occup Ther. 2001;68(5):280–9.

206. Hart JM, Pietrosimone B, Hertel J, Ingersoll CD. Quadriceps activation following knee injuries: a systematic review. J Athl Train. 2010;45(1): 87–97.
207. Grooms D, Simon JE, Onate JA; Athletic Trainers Osteoarthritis Consortium. Neuroplasticity and patient-reported outcomes after anterior cruciate ligament reconstruction. Ohio University Athletic Training. 2016.
208. Grooms DR, Myer GD. Upgraded hardware horizontal line What about the software? Brain updates for return to play following ACL reconstruction. Br J Sports Med. 2017;51(5):418–9.
209. Grooms DR, Onate JA. Neuroscience application to noncontact anterior cruciate ligament injury prevention. Sports Health. 2015;8(2):149–52.
210. Roberts D, Friden T, Zatterstrom R, Lindstrand A, Moritz U. Proprioception in people with anterior cruciate ligament-deficient knees: comparison of symptomatic and asymptomatic patients. J Orthop Sports Phys Ther. 1999;29(10):587–94.
211. Lepley AS, Gribble PA, Thomas AC, Tevald MA, Sohn DH, Pietrosimone BG. Quadriceps neural alterations in anterior cruciate ligament reconstructed patients: a 6-month longitudinal investigation. Scand J Med Sci Sports. 2015;25(6):828–39.
212. Pietrosimone BG, Lepley AS, Ericksen HM, Clements A, Sohn DH, Gribble PA. Neural excitability alterations after anterior cruciate ligament reconstruction. J Athl Train. 2015;50(6):665–74.
213. Houck JR, Wilding GE, Gupta R, De Haven KE, Maloney M. Analysis of EMG patterns of control subjects and subjects with ACL deficiency during an unanticipated walking cut task. Gait Posture. 2007;25(4):628–38.
214. Negahban H, Ahmadi P, Salehi R, Mehravar M, Goharpey S. Attentional demands of postural control during single leg stance in patients with anterior cruciate ligament reconstruction. Neurosci Lett. 2013;556:118–23.
215. O'Connell M, George K, Stock D. Postural sway and balance testing: a comparison of normal and anterior cruciate ligament deficient knees. Gait Posture. 1998;8(2):136–42.
216. Hoffman M, Schrader J, Koceja D. An investigation of postural control in postoperative anterior cruciate ligament reconstruction patients. J Athl Train. 1999;34(2):130–6.
217. Mattacola CG, Perrin DH, Gansneder BM, Gieck JH, Saliba EN, McCue FC. Strength, functional outcome, and postural stability after anterior cruciate ligament reconstruction. J Athl Train. 2002;37(3):262–8.
218. McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. Med Sci Sports Exerc. 1999;31(7):959–68.
219. McLean SG, Lipfert SW, van den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. Med Sci Sports Exerc. 2004;36(6):1008–16.
220. Swanik CB, Lephart SM, Giraldo JL, DeMont RG, Fu FH. Reactive muscle firing of anterior cruciate ligament-injured females during functional activities. J Athl Train. 1999;34(2):121–9.
221. Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Use of an overhead goal alters vertical jump performance and biomechanics. J Strength Cond Res. 2005;19(2):394–9.
222. Wikstrom E, Tillman M, Schenker S, Borsa P. Failed jump landing trials: deficits in neuromuscular control. Scand J Med Sci Sports. 2008;18(1):55–61.
223. Cortes N, Blount E, Ringleb S, Onate JA. Soccer-specific video simulation for improving movement assessment. Sports Biomech. 2011;10(1):22–34.
224. McLean SG, Huang X, van den Bogert AJ. Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. Clin Biomech. 2005;20(8):863–70.
225. Pollard CD, Heiderscheit BC, van Emmerik RE, Hamill J. Gender differences in lower extremity coupling variability during an unanticipated cutting maneuver. J Appl Biomech. 2005;21(2):143–52.
226. Brown TN, Palmieri-Smith RM, McLean SG. Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: implications for anterior cruciate ligament injury. Br J Sports Med. 2009;43(13):1049–56.
227. Pollard CD, Davis IM, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. Clin Biomech. 2004;19(10):1022–31.
228. Almonroeder TG, Kernozek T, Cobb S, et al. Cognitive demands influence lower extremity mechanics during a drop vertical jump task in female athletes. J Orthop Sports Phys Ther. 2018;48(5):381–7.
229. Besier TF, Lloyd DG, Ackland TR, et al. Anticipatory effects on knee joint loading during running and cutting maneuvers. Med Sci Sports Exerc. 2001;33(7):1176–81.
230. Meinerz CM, Malloy P, Geiser CF, et al. Anticipatory effects on lower extremity neuromechanics during a cutting task. J Athl Train. 2015;50(9):905–13.
231. Monfort SM, Comstock RD, Collins CL, Onate JA, Best TM, Chaudhari AM. Association between ball-handling versus defending actions and acute noncontact lower extremity injuries in high school basketball and soccer. Am J Sports Med. 2015;43(4):802–7.
232. Dingenen B, Janssens L, Luyckx T, Claes S, Bellemans J, Staes FF. Lower extremity muscle activation onset times during the transition from double-leg stance to single-leg stance in anterior cruciate ligament injured subjects. Hum Mov Sci. 2015;44:234–45.
233. Dingenen B, Janssens L, Luyckx T, Claes S, Bellemans J, Staes FF. Postural stability during the transition from double-leg stance to single-leg stance in anterior cruciate ligament injured subjects. Clin Biomech. 2015;30(3):283–9.

234. Sadoghi P, von Keudell A, Vavken P. Effectiveness of anterior cruciate ligament injury prevention training programs. J Bone Joint Surg. 2012;94(9):769–76.
235. Ardern CL, Taylor NF, Feller JA, Webster KE. Return-to-sport outcomes at 2 to 7 years after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2012;40(1):41–8.
236. Zabala ME, Favre J, Scanlan SF, Donahue J, Andriacchi TP. Three-dimensional knee moments of ACL reconstructed and control subjects during gait, stair ascent, and stair descent. J Biomech. 2013;46(3):515–20.
237. Wilkerson GB. Neurocognitive reaction time predicts lower extremity sprains and strains. Int J Athl Ther Train. 2012;17(6):4–9.
238. Appelbaum LG, Cain MS, Schroeder JE, Darling EF, Mitroff SR. Stroboscopic visual training improves information encoding in short-term memory. Atten Percept Psychophys. 2012;74:1–11.
239. Appelbaum LG, Schroeder JE, Cain MS, Mitroff SR. Improved visual cognition through stroboscopic training. Front Psychol. 2011;2:276.
240. Swanik CBSK, Huxel KC, Tiemey RT, Hamstra KL, Hillstrom HJ. EMG and kinematic analysis of drop jumps from an unknown height: a mechanism for non-contact injuries. J Athl Train. 2003;38(2):S18.
241. Swanik K, Swanik C, Huxel K, Huston K, Fierney R, Hillerstrom H. Gender difference in drop jumps from unknown heights: an EMG and kinematic analysis. J Athl Train. 2004;39:S14–5.
242. Mitroff SFP, Bennett D, Yoo H, Reichow A. Enhancing ice hockey skills through stroboscopic visual training: a pilot study. Athl Train Sports Health Care. 2013;5(6):261–4.
243. Smith TQ, Mitroff SR. Stroboscopic training enhances anticipatory timing. Int J Exerc Sci. 2012;5(4):4.
244. Di Stasi S, Myer GD, Hewett TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. J Orthop Sports Phys Ther. 2013;43(11):777–92.
245. Kim KM, Kim JS, Grooms DR. Stroboscopic vision to induce sensory reweighting during postural control. J Sport Rehabil. 2017;26:1–11.
246. Harpham JA, Mihalik JP, Littleton AC, Frank BS, Guskiewicz KM. The effect of visual and sensory performance on head impact biomechanics in college football players. Ann Biomed Eng. 2013;42(1): 1–10.
247. Mihalik JP, Blackburn JT, Greenwald RM, Cantu RC, Marshall SW, Guskiewicz KM. Collision type and player anticipation affect head impact severity among youth ice hockey players. Pediatrics. 2010;125(6):E1394–401.
248. Houck JR, De Haven KE, Maloney M. Influence of anticipation on movement patterns in subjects with ACL deficiency classified as noncopers. J Orthop Sports Phys Ther. 2007;37(2):56–64.
249. Pelletier R, Higgins J, Bourbonnais D. Is neuroplasticity in the central nervous system the missing link to our understanding of chronic musculoskeletal disorders? BMC Musculoskelet Disord. 2015;16(1):25.
250. Ross LM, Register-Mihalik JK, Mihalik JP, et al. Effects of a single-task versus a dual-task paradigm on cognition and balance in healthy subjects. J Sport Rehabil. 2011;20:296–310.
251. Teel EF, Register-Mihalik JK, Troy Blackburn J, Guskiewicz KM. Balance and cognitive performance during a dual-task: preliminary implications for use in concussion assessment. J Sci Med Sport. 2013;16:190–4.
252. Verburgh L, Scherder EJ, Van Lange PA, Oosterlaan J. Do elite and amateur soccer players outperform non-athletes on neurocognitive functioning? A study among 8-12 year old children. PLoS One. 2016;11:e0165741.
253. Alhilali LM, Yaeger K, Collins M, Fakhran S. Detection of central white matter injury underlying vestibulopathy after mild traumatic brain injury. Radiology. 2014;272:224–32.
254. Schubert MC, Minor LB. Vestibulo-ocular physiology underlying vestibular hypofunction. Phys Ther. 2004;84:373–85.
255. Hillier S, McDonnell M. Is vestibular rehabilitation effective in improving dizziness and function after unilateral peripheral vestibular hypofunction? An abridged version of a Cochrane Review. Eur J Phys Rehabil Med. 2016;52:541–56.

Return to Sport for Soccer and Basketball

17

Frank R. Noyes and Sue Barber-Westin

17.1 Introduction

Soccer and basketball are the most popular sports worldwide. A survey of 18 markets across the Americas, Europe, the Middle East, and Asia conducted in 2017 by The Nielsen Company showed soccer had the highest percentage of respondents either "interested" or "very interested" in the sport compared with 10 other sports (43%, 736 million people) followed by basketball (36%, 626 million people) [1]. Unfortunately, lower extremity injuries are common in these sports in athletes of all ages and playing levels [2–11]. Recent investigations [2, 3, 5] used a Web-based sports injury surveillance system for 8 academic years to track soccer and basketball injuries from 100 high schools. In girls, a total of 3242 time-loss soccer injuries were sustained (national estimate, 1,874,022 injuries) and 2930 basketball injuries were reported (national estimate, 775,942 injuries). In boys, 2912 time-loss injuries in soccer were sustained (national estimate, 1,507,166 injuries). Knee-related injuries in soccer occurred in 478 girls (national estimate, 259,587 injuries), and ligament sprains (knee/ankle) were the most common diagnosis in games, accounting for 34.5% of all injuries. Knee injuries in soccer occurred in 242 boys (national estimate, 114,384), and ligament sprains were the most common diagnosis in games (26%). Knee injuries are also among the most common of all injuries sustained in collegiate basketball [11].

Anterior cruciate ligament (ACL) tears occurring in soccer and basketball players have been noted extensively with large surveillance systems [12–15]. Return to sport (RTS) after this severe injury entails many months of rehabilitation that must incorporate strength, neuromuscular, proprioceptive, and, finally, sports-specific agility and skills training. There is little information available on proven programs to return soccer and basketball players to competition after ACL tears and reconstruction [16, 17]

Our center devised training programs for soccer [18] (Sportsmetrics Soccer) and basketball [19] (Sportsmetrics Basketball) that implemented the components of Sportsmetrics (see Chap. 14) along with other exercises and drills designed to improve dynamic balance, agility, speed, strength, and aerobic conditioning. The programs offer a unique blend of neuromuscular retraining and sport-specific enhancement tasks to both improve player strength, power, skill, and aerobic fitness and decrease the risk of a knee ligament injury. We encourage all athletes who have suffered serious knee injuries, treated either conser-

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_17

vatively or operatively, to complete these programs as end-stage rehabilitation before resuming team competition. In athletes who undego ACL reconstruction, the rehabilitation principles and programs are detailed in Chaps. 11 and 14. Patients should have completed the running and agility program and the basic plyometric training program described in Chap. 14 before beginning Sportsmetrics Soccer or Sportsmetrics Basketball. All of our postoperative rehabilitation programs for major knee operations are designed to restore strength, balance, proprioception, and neuromuscular indices required in athletes who wish to resume sports that require cutting, pivoting, twisting, turning, and landing [20–24].

A series of tests may be conducted before the first training session and after the final (18th) session to determine if further improvements are required in balance, agility, speed, or strength. We use the cost-effective field tests for soccer players and basketball players described later in this chapter (see Sect. 17.5). Sportsmetrics Soccer and Sportsmetrics Basketball begin with a 10-min dynamic warm-up and then move to plyometric exercises described in Chap. 14. Training then involves sport-specific agility, speed, and aerobic conditioning drills described below. Strength and static flexibility exercises are also performed as described in Chap. 14. These programs were conducted and validated in high school female athletes [18, 19]. For older athletes and those involved in elite national and international competition, further training is expected to be required to return to the highest level of competition. A variety of resources are available that describe training and conditioning concepts for elite athletes [17, 25–40].

17.2 Techniques for Running, Agility, and Reaction Drills

Common playing situations noted at the time of ACL injury involve landing from a jump or a change of direction such as a cut or pivot, combined with deceleration where the knee is near full extension and the foot is firmly fixed flat on the playing surface [41, 42]. The center of mass of the body is often noted to be far from the area of foot-ground contact. Valgus collapse at the knee is frequently reported, although it is unknown whether this abnormal position occurs before, during, or just after the ACL rupture.

Rehabilitation and sport-specific training programs for patients recovering from ACL reconstruction or other major knee operations should include instruction to avoid at-risk situations during landing from a jump, decelerating, cutting, and pivoting maneuvers [43, 44]. The programs described in this chapter involve a number of drills designed to familiarize and enhance the athletes' ability to perform planned as well as unanticipated changes of direction. Awareness training techniques including verbal and visual feedback are considered vital to successfully correct form for the most difficult athletic maneuvers. The combination of verbal cues from an expert instructor and feedback of videotape samples of the athlete performing a task has been shown to reduce impact loads and improve maximum knee flexion during jump-landing [45–47]. Recommended instructions for agility and reaction drills include the following (Fig. 17.1) [41, 44, 49–52]:

1. Regardless of the direction, the first step should be short. Keep the toes pointed forward.
2. Maintain, as much as possible, control of the body's center of gravity throughout the drill.
3. Keep an erect posture with a stable trunk and avoid excessive anterior pelvic tilt and rounded shoulders.
4. Keep the head and eyes up, looking straight ahead.
5. Keep the body weight evenly distributed over the balls of the feet.
6. Maintain the same angle of hip, knee, and ankle flexion throughout the drill, including during changes in direction. Knee flexion should be >30°.
7. Avoid a valgus lower limb position.
8. Keep the knees over the ankles and do not allow them to extend over the toes.
9. During deceleration, use three short steps to reduce speed instead of one step.

Fig. 17.1 (**a**) Valgus knee position on a side cut, (**b**) loss of hip and knee flexion angles during deceleration just prior to a side cut, (**c**) knee hyperextension and foot far in front of center of body mass upon planting for a side cut [48]

10. During a sidestep cut, bring the foot to the midline to plant and keep the torso upright, with no rotation, pointed in the general direction the athlete wishes to travel.
11. Videotape the athlete while they perform drills and exercises to show techniques that require correction.
12. The instructor should demonstrate the correct technique as often as required, asking the athlete to imitate what they see.

17.3 Soccer (Table 17.1)

17.3.1 Agility and Reaction Drills

17.3.1.1 Serpentine Run

Arrange six cones in a zigzag pattern within a 15 × 37 ft (4.6 × 11.3 m) area (Fig. 17.2). The athlete begins on the left of the first cone and sprints across to the next cone in the pattern. Upon reaching the second cone, the athlete decelerates and goes around the cone without stopping. The athlete reaches down and taps the top of the cone, then immediately accelerates to the next cone, and repeats the decelerate/tap/accelerate sequence. Once the last cone is reached, an instructor presses the athlete and forces them to cut either right or left. The athlete then jogs back to the starting position.

17.3.1.2 Wheel Drill: Listen to Instructor

Arrange four cones, each within lunging distance of the athlete, in the 12, 3, 6, and 9 o'clock positions (Fig. 17.3). The athlete stands in the middle facing the 12 o'clock cone, which is the neutral position. The instructor calls out 1 of the 4 positions, and athlete responds by lunging toward that cone and immediately returning to neutral. At the 12 and 6 o'clock positions, the athlete may lunge with either leg. At the 3 o'clock position, the athlete lunges with the left leg, and at the 9 o'clock position, the athlete lunges with the right leg.

17.3.1.3 Shuttle Run

Arrange seven cones in a zigzag pattern within a 10 × 30 ft (3.0 × 9.1 m) area (Fig. 17.4). The athlete begins on the left of the first cone and sprints across to the next cone in the pattern. Upon approaching the second cone, the athlete decelerates and performs a sharp cut in order to tap the top

Table 17.1 Sportsmetrics Soccer training program[a]

Component	Session no.	Exercise	Duration
Agility, reaction	1–3	Serpentine run	¼ field, 3 reps
	1–3	Wheel drill: listen to instructor	30 s, 2 reps
	4–6	Shuttle run	¼ field, 3 reps
	4–6	Sprint-stop feet-listen	30 s, 2 reps
	7–9	Square drill	30′ × 30′ (9.1 × 9.1 m) box, 2 reps
	7–9	Sprint-quick feet-listen	45 s, 2 reps
	10–12	Nebraska drill	30′ (9.1 m) long, 4 reps
	10–12	Reaction drill-watch instructor point	45 s, 2 reps
	13–15	Illinois drill	15′ × 10′ (4.6 × 3.0 m), 4 reps
	13–15	Reaction mirror drill, pressing	60 s, 2 reps
	16–18	T-drill: 5–10-5	4 reps
	16–18	Advanced wheel drill: listen to instructor	60 s, 2 reps
Acceleration, speed, endurance	1–3	Partner push-offs, hold 5 s	5 reps
	1–3	Sprint-backpedal	½ field or 50 yards (45.7 m), 5 reps
	1–3	Jog	4 laps around field (1280 yards, 1170 m)
	4–6	Acceleration with band	Go to 10-yard (9.1 m) line
	4–6	Sprint with ground touches-backpedal	½ field or 50 yards (45.7 m), 5 reps
	4–6	100 yards (91.4 m) shuttle	3 × 100 (300 yards, 274 m), 4 reps
	7–9	Partner push-offs, hold 10 s	5 reps
	7–9	½ Eagle into sprint, jog back	½ field or 50 yards (45.7 m), 6 reps
	7–9	50 yards (45.7 m) shuttle	Up and back × 3 (300 yards, 274 m), 4 reps
	10–12	Acceleration with band	Go to 20-yard (18.3 m) line
	10–12	Box drill, sprint-90°-backpedal	½ field, 3 reps
	10–12	50-yard (45.7 m) cone drill: 10 yards (9.1 m)-back, 20 yards (18.3 m)-back, 30 yards (27.4 m)-back, 40 yards (36.6 m)-back, 50 yards (45.7 m)-back	4 reps
	13–15	Partner push offs, hold 15 s	5 reps
	13–15	Sprint-180°-backpedal	½ field or 50 yards (45.7 m), 7 reps
	13–15	Jingle Jangle, 20 yards (18.3 m)	Up and back × 5 (200 yards, 183 m), 5 reps
	16–18	Acceleration with band	Go to 30-yard (27.4 m) line
	16–18	Sprint-360°-sprint	½ field or 50 yards (45.7 m), 7 reps
	16–18	Jingle Jangle, 10 yards (9.1 m)	Up and back × 5 (100 yards, 91 m), 6 reps
Ladders, quick feet, additional jumps	1–3	Ladder: up-up and back-back	2 reps
	1–3	Dot drill: double leg jumps	5 reps × 3
	4–6	Ladder: toe touches	2 reps
	4–6	Dot drill: add split leg jumps	5 reps × 3
	7–9	Ladder: outside foot in	2 reps
	7–9	Dot drill: add 180° split leg jump	5 reps × 3
	10–12	Ladder: in-in, out-out	2 reps
	10–12	Dot drill: add single-leg hops	5 reps × 3
	13–15	Ladder: up-up and back-back	2 reps
	13–15	Dot drill: combo all jumps	5 reps × 3
	16–18	Ladder: 1 foot forward, 1 foot backward	2 reps
	16–18	Dot drill: combo all jumps	5 reps × 4

Table 17.1 (continued)

Component	Session no.	Exercise	Duration
Strength training	1–18	Resistance band: squats	Perform all exercise for 30 s during sessions 1–6, for 45 s during sessions 7–12, and for 60 s during sessions 13–18
		Resistance band: lunges	
		Single-leg heel raise	
		Prone hamstring (with partner resistance)	
		Supine hamstring bridge	
		Abdominals of choice	
		Hip flexor: resistance band knee drive (partner)	
		Hip abductor: resistance band kicking (partner)	
		Resistance band: arm swing	
		Wall sits	

[a]From Barber-Westin and Noyes [48]

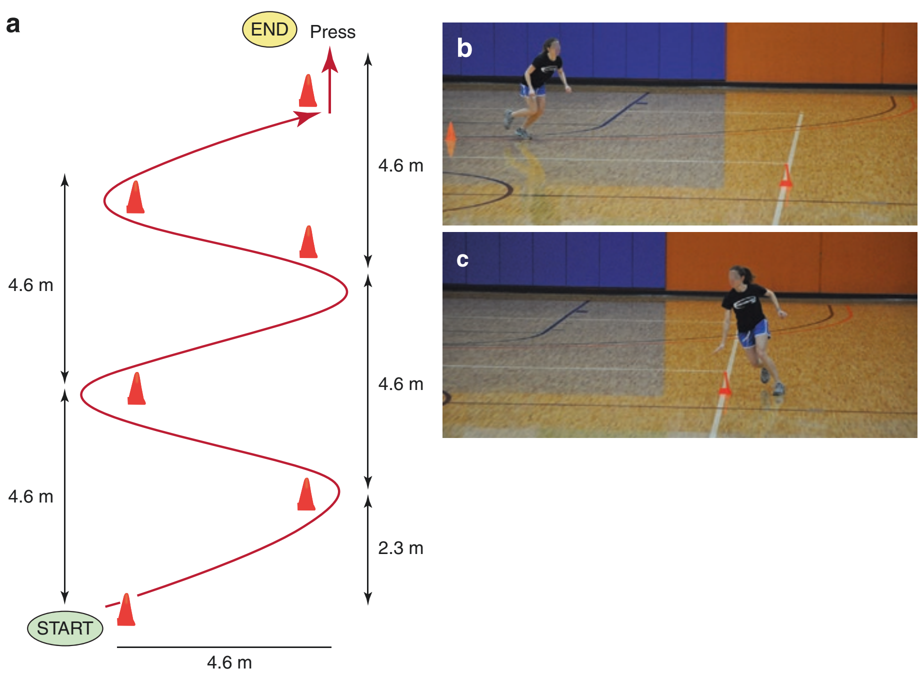


Fig. 17.2 Serpentine run: (**a**) course and (**b**, **c**) direction [48]

of the cone once it is reached. As soon as the second cone is tapped, the athlete immediately accelerates across in a straight line to the next cone and repeats the decelerate/tap/accelerate sequence until the last cone in the pattern is reached. The instructor incorporates a ball pass during the cutting maneuvers as shown in Fig. 17.4. Once the last cone is reached, the athlete sprints to midfield and then jogs back to the starting position.

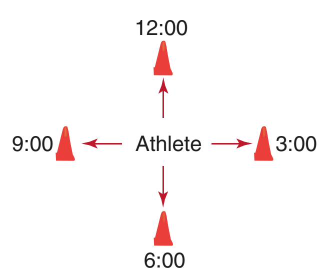


Fig. 17.3 Wheel drill [48]

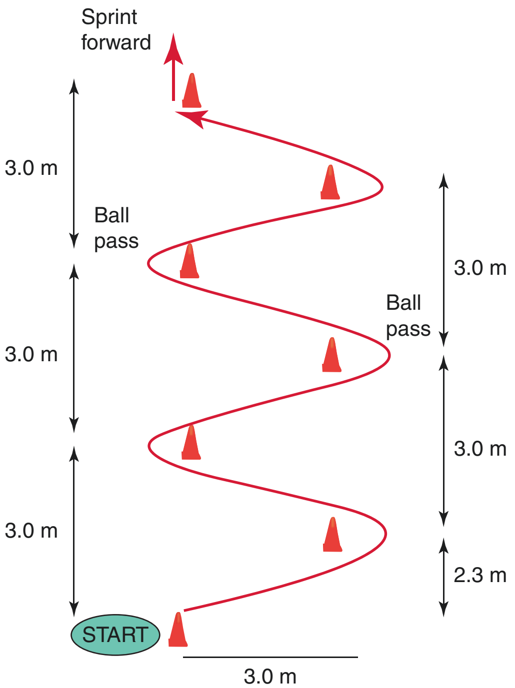


Fig. 17.4 Shuttle run [48]

17.3.1.4 Sprint-Stop Feet-Listen to Instructor

The athlete begins sprinting the length of the field. During the sprint, the instructor commands "stop" at any time, at which point the athlete must immediately stop, hold still, and wait to begin sprinting until the instructor commands "go."

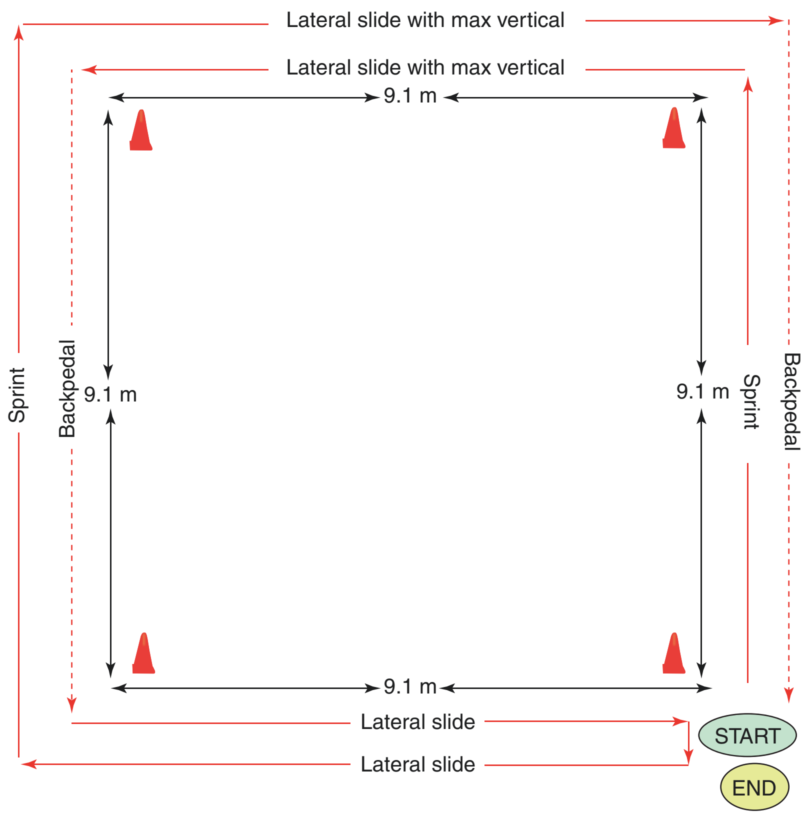
17.3.1.5 Sprint-Quick Feet-Listen to Instructor

This drill is the same as the sprint-stop feet-listen drill, except when the instructor commands "stop," the athlete must keep their feet moving quickly in the same spot until the instructor commands "go."

17.3.1.6 Square Drill

The athlete begins at the back corner of a 30 × 30 ft square (9.1 × 9.1 m, Fig. 17.5). Moving around the outside of the square, the athlete sprints forward, performs a lateral slide across (while jumping up to a maximum vertical jump between each slide), backpedals to the backside,

Fig. 17.5 Square drill [48]



and performs a lateral slide across the back of the square to the starting position. Then, the athlete reverses the direction and repeats, starting with the lateral slide. A ball may be thrown in at any time for a head ball or ground pass.

17.3.1.7 Nebraska Agility Drill

Arrange two cones 30 ft (9.1 m) apart (Fig. 17.6). The athlete begins on the right side of the first cone and sprints to the left side of the second cone. The right hand is placed down on the second cone, and a pivot is done around the cone until the athlete is facing the first cone. The athlete then sprints to the right side of the first cone and places their left hand down to pivot around the cone until they are facing the second cone (completing a figure-8 sequence around the cones). Staying on the right side of both cones and close to the cones, the athlete sprints forward to the second cone. Upon reach-

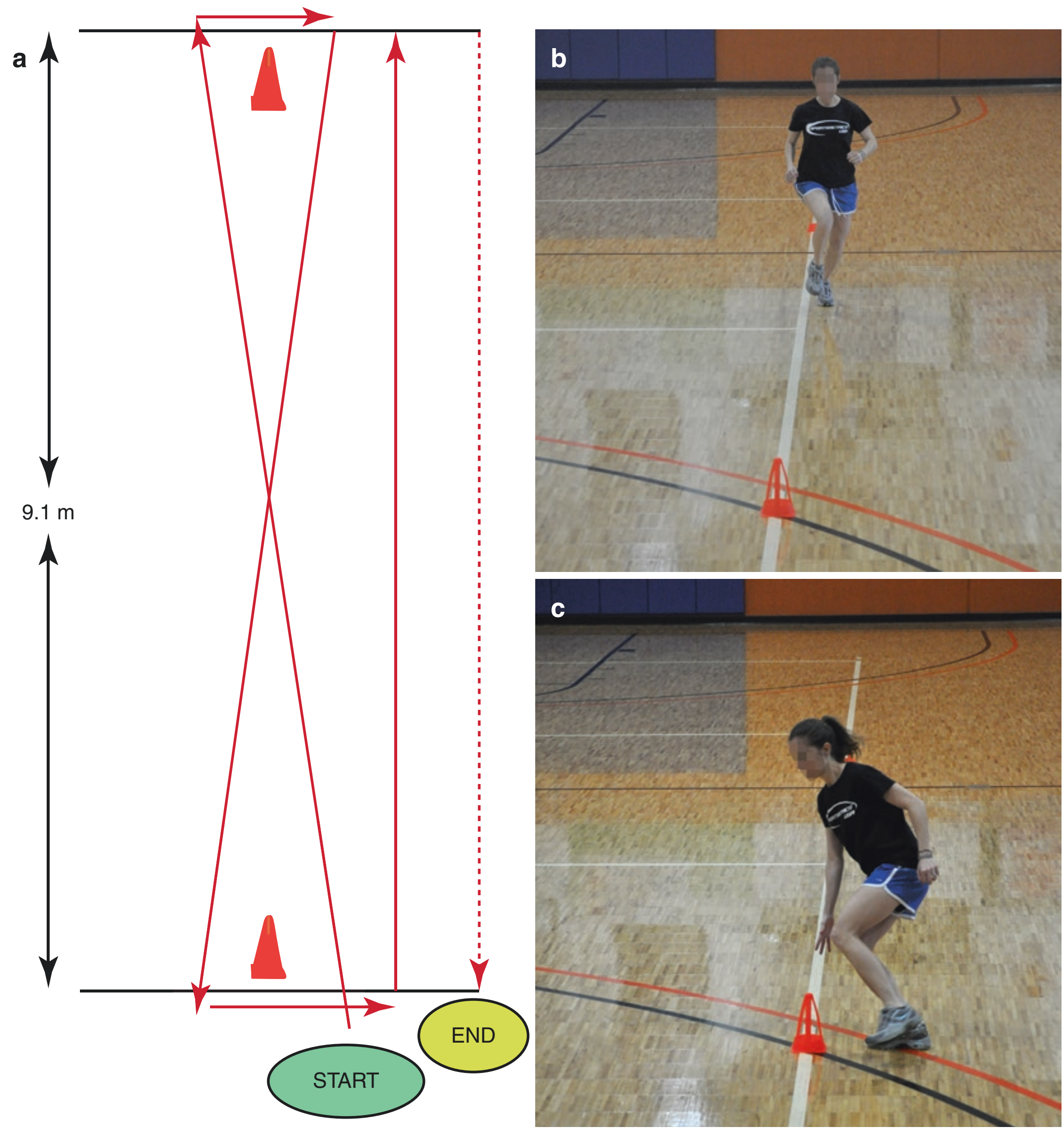


Fig. 17.6 Nebraska agility drill: (**a**) course and (**b**, **c**) direction. *Solid lines* indicate forward sprinting; *dotted line* indicates backpedaling [48]

ing that cone, the athlete backpedals to the starting line.

17.3.1.8 Reaction Drill-Watch Instructor Point

The athletes spread out along the soccer field, facing the instructor who is standing on the end line. The instructor uses hand motions and points toward the direction in which the athletes run. For example, if the instructor points straight forward, the athletes backpedal away from the instructor. If the instructor points right, the athletes side shuffle to their left. If the instructor points diagonally to the right, the athletes backpedal diagonally to their left.

17.3.1.9 Reaction Mirror Drill-Partner Pressing

Two athletes stand 3–4 ft (0.9–1.2 m) apart, facing each other. One athlete leads the exercise, while the other mirrors the partner. The leading athlete may sprint forward, backpedal, or shuffle to one side or another quickly. The mirror partner follows the lead as fast as possible, moving in the exact same direction.

17.3.1.10 Illinois Drill

Arrange four cones in a 30 × 30 ft (9.1 × 9.1 m) square (Fig. 17.7). Place four cones in a line in the center of the square, approximately 3–4 ft (0.9–1.2 m) apart. Beginning at the bottom left cone, the athlete sprints forward to the top left cone. While reaching down to tap the top of the cone, a tight cut is done around the cone. The athlete sprints to the first middle cone and then zigzags, cutting around each of the four cones in the middle, bending down to tap the top of each cone. After the athlete rounds the last of the four middle cones, they sprint to the bottom right cone, cut around the cone while tapping the top of the cone, and sprint through the last cone. The athlete then jogs to the left to the starting position.

17.3.1.11 T-Drill: 5–10-5

Arrange three cones and a start/finish marker so that they form the capital letter "T" (Fig. 17.8). The first cone should be placed 30 ft (9.1 m) in front of the start/finish marker. The two remaining cones should be placed so that each is exactly 15 ft (4.6 m) from (and in line with) the

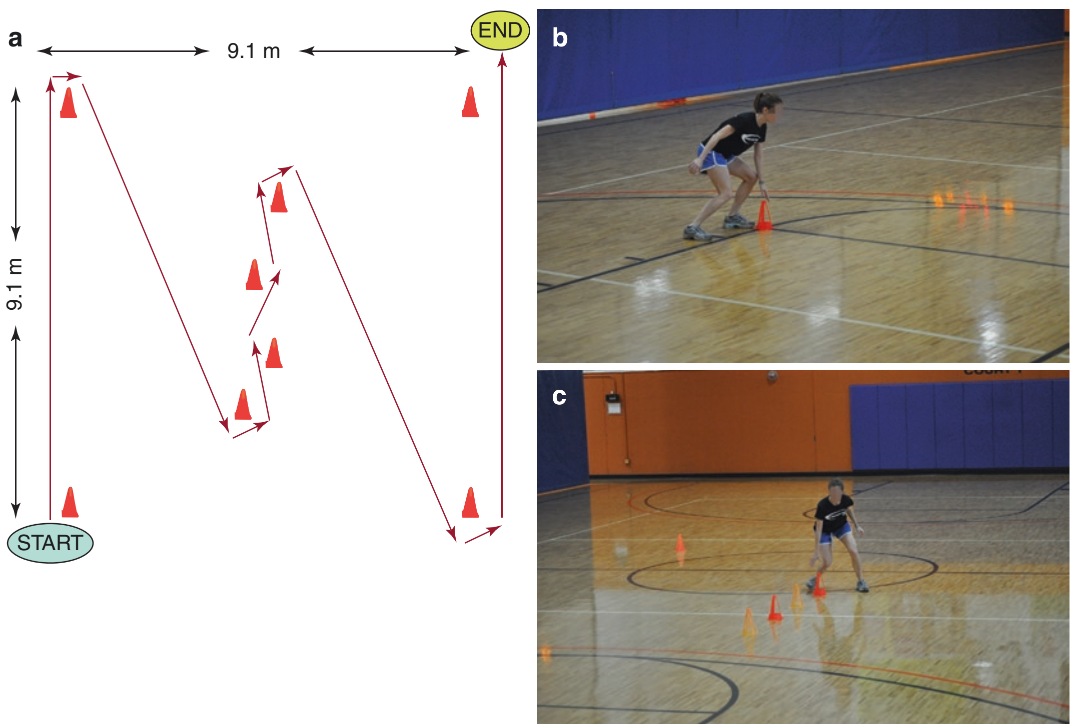


Fig. 17.7 Illinois drill: (**a**) course and (**b**, **c**) direction [48]

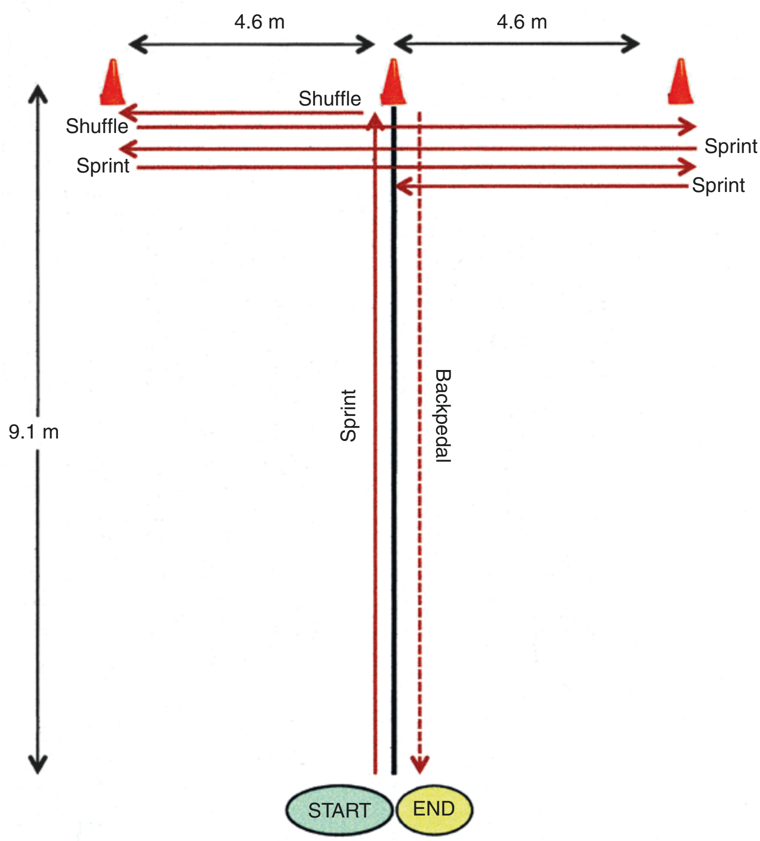


Fig. 17.8 T-drill. The shuffles and sprints at the top of the "T" are done in a straight line. The figure depicts the 5 segments individually for illustrative purposes only [48]

first cone. Starting at the base of the "T," the athlete sprints forward to the cone straight ahead. Upon reaching the cone, the athlete immediately shuffles left, ensuring that the feet do not cross at any point during the shuffle. The top of the left cone is tapped, and the athlete immediately shuffles right, passing the middle cone and tapping the top of the cone of the right. Then, the athlete immediately sprints to the far left cone, taps the cone, sprints to the far right cone, taps that cone, sprints to the center cone, taps that cone, and backpedals to the starting position.

17.3.1.12 Advanced Wheel Drill: Listen to Instructor

Arrange eight cones, each approximately 7 ft (2.1 m) from center. Place two cones at the 12 o'clock position, two at the 3 o'clock position, two at the 6 o'clock position, and two at the 9 o'clock position. The athlete begins facing the 12 o'clock cones, with "quick feet" constantly and quickly moving under the body. The instructor calls 1 of the 4 positions, and the athlete responds by immediately running between the two cones and holding the quick feet position until instructor calls "back." The athlete returns to the center, keeping their feet moving.

17.3.2 Acceleration, Speed, and Endurance Drills

17.3.2.1 Partner Push-Offs

Two athletes of similar body weight form partners, one who will sprint and the other who will resist the sprinter. The resister places their hands on the shoulders of the sprinter (Fig. 17.9). The sprinter assumes a starting position and leans forward against the resister. On command, the sprinter begins sprinting against the resister, driving their knees upward and forward, attempting to move forward. The resister places enough resistance against the sprinter to keep them stationary

Fig. 17.9 Partner push-offs [48]

or moving only slowly forward. The sprinter counts out loud for 5, 10, or 15 s. When the sprinter has finished counting, the resister rolls off to the side and allows the sprinter to accelerate forward for five to ten strides. Then, the partners switch rolls and complete the drill again.

17.3.2.2 Acceleration with Band

Two athletes of similar body weight form partners. Both athletes are positioned inside a looped resistance band, one behind the other, facing the same direction. The partner in front will sprint and the partner in back will resist the sprinter. On command, the sprinter begins sprinting forward at full speed, while the resister leans back and holds the band to provide resistance. The distance between the sprinter and resister should remain constant throughout the entire sprint.

17.3.2.3 Sprint with Ground Touches-Backpedal

The athlete begins on the end line and sprints forward to a cone placed 15 yards (13.7 m) away. The athlete reaches down quickly, without stopping, and touches the ground next to the cone. The feet are kept underneath the body while bending at the knees and hips to reach down. The athlete sprints another 15 yards (13.7 m) and repeats the ground touch. Sprinting is continued until midfield is reached, and then the athlete backpedals at ¾ speed to the starting position.

17.3.2.4 ¼ Eagle Sprint-Backpedal

The athlete begins facing a sideline in an athletic ready position. The athlete performs a jump sequence by first jumping to face midfield, then jumping back to face the sideline, then jumping with their back to the field, and then jumping back to face the sideline. This jump sequence is repeated until the instructor commands "go" at which time they sprint to midfield and then backpedal to the starting position.

17.3.2.5 Box Drill, Sprint-90°-Backpedal

The athlete begins at the bottom right corner of the penalty box (Fig. 17.10). Upon command, they sprint forward to the top of the box and perform a 90° turn by pivoting on the left foot and turning over the right shoulder. The athlete should be facing the right-hand sideline. They backpedal the length of the top of the box and, at the corner, make a 90° turn by pivoting on the right foot and turning over the right shoulder. The athlete should be facing the end line. They then sprint to the end line and make another 90° turn, pivoting on the left foot and turning over the right shoulder. The athlete backpedals to the starting position. They retrace the square by immediately sprinting to the end line, making a 90° pivot on the right foot and turning over the left shoulder, backpedaling to the top of the penalty box, making a 90° pivot on the left foot and turning over the left shoulder, sprint to the other side of the penalty box, and end with a 90° pivot on the right foot and turn over the left shoulder to backpedal to the finish.

17.3.2.6 Sprint-180°-Backpedal

The athlete begins at the end line, sprints to the penalty line, and completes a 180° turn, keeping the feet and knees directly under the body and taking short, choppy steps. The athlete backpedals to the midline and then immediately sprints back toward the end line. Upon reaching the pen-

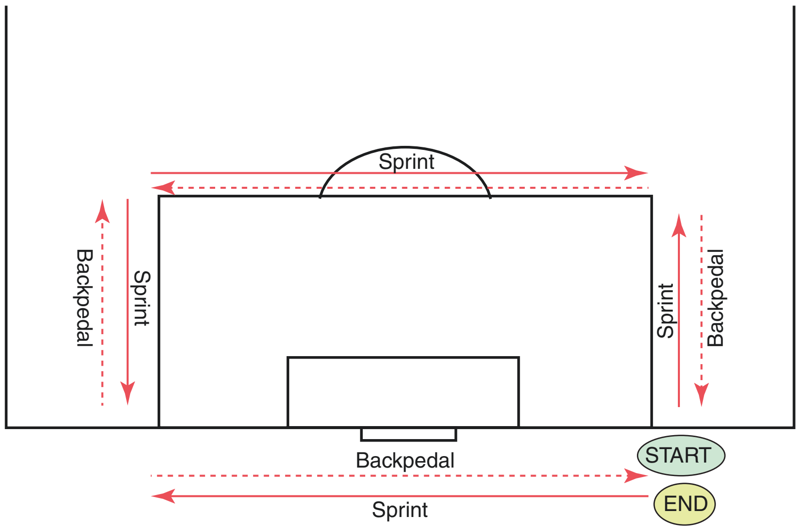


Fig. 17.10 Box drill, sprint-90°-backpedal [48]

alty line, the athlete completes another 180° turn and backpedals to the starting position.

17.3.2.7 Jingle Jangle

The athlete sprints a series of five repetitions of 20 yards (18.3 m), up and back (Fig. 17.11).

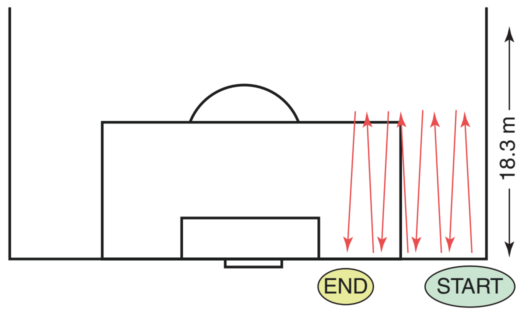


Fig. 17.11 Jingle Jangle drill [48]

17.3.2.8 Sprint-360°-Sprint, Jog Back

The athlete begins at the end line, sprints to the penalty line, and completes a 360° turn, keeping the feet and knees directly under the body and taking short, choppy steps. The athlete sprints to the midline, backpedals to the penalty line, completes another 360° turn, and backpedals to the starting position.

17.3.3 Ladders, Additional Jump Drills

17.3.3.1 Ladder: Up-Up and Back-Back

A 15-ft (4.6 m) ladder is placed along the sideline (Fig. 17.12). The athlete begins at the left end of the ladder and steps the right foot forward and diagonally over the ladder into the first square, followed quickly by the left foot. As soon as the left foot crosses the ladder, the athlete steps the right foot backward and diagonally (back over the ladder), again followed quickly by the left foot. This pattern is continued until the other end of the ladder is reached. Once the end of the ladder is reached, the same pattern is completed back to the starting position, leading with the left foot.

17.3.3.2 Ladder: Toe Touches

The athlete begins in front of the ladder with the right toe touching one side of the ladder and left foot on the ground. On command, the athlete alternates toe touches from left toe to right toe. The feet are switched in the air as quickly as possible. Only the toes should touch the ladder. This exercise may be done with a soccer ball instead of a ladder.

17.3.3.3 Ladder: Outside Foot In

The athlete begins at the bottom right of the ladder and steps the right foot in the first square of the ladder (Fig. 17.13). Then, the athlete steps the

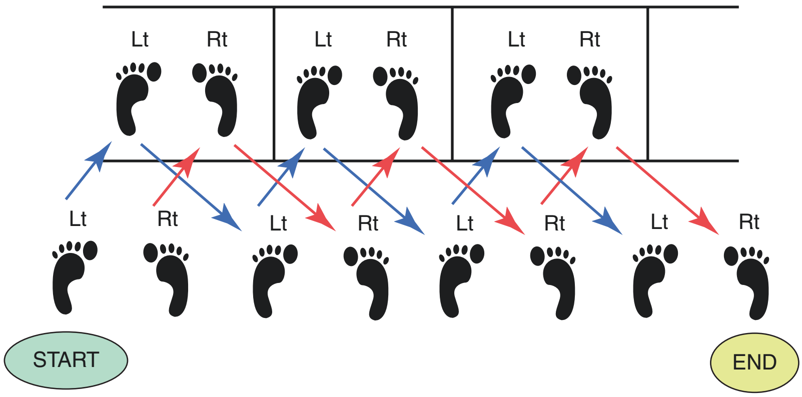


Fig. 17.12 Ladder: up-up and back-back. Only a portion of the 4.6-m ladder is shown for illustrative purposes [48]

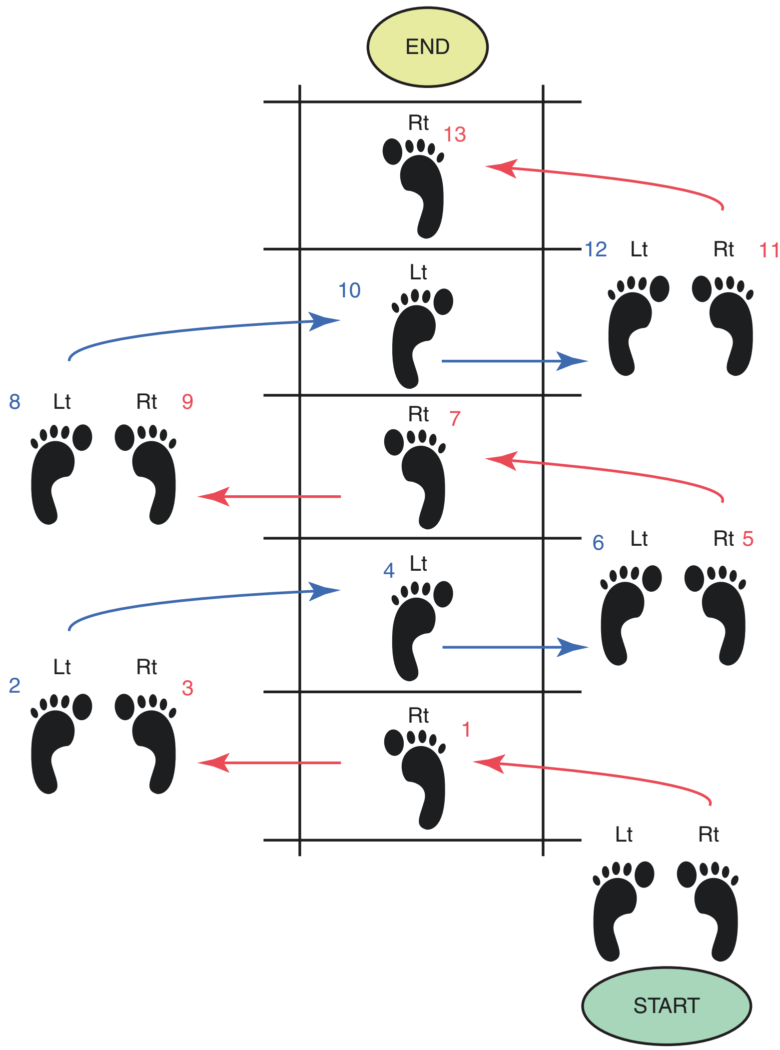


Fig. 17.13 Ladder: outside foot in. Only a portion of the 4.6-m ladder is shown for illustrative purposes [48]

left foot to the left outside of the first square, followed by the right foot. Next, the athlete steps the left foot in the second square, followed by the right foot outside the ladder and then the left foot. This pattern is continued to the end of the ladder and is then repeated, moving backward.

17.3.3.4 Ladder: In-In, Out-Out

The athlete begins at the bottom of the ladder, with the feet spread apart outside of the first square as shown in Fig. 17.14. They step the right foot forward into the first ladder square, followed quickly by the left foot. As soon as the left foot touches down in the ladder square, the right foot steps forward and laterally (to the outside right of the ladder) so that it is parallel to the ladder and in line with the ladder's rung. Once the right foot touches down outside of the ladder, the left foot steps forward and laterally (to the outside left of the ladder) so that it too is parallel to the ladder and in line with the rung. Once the left foot is down, the right foot steps forward and laterally into the next ladder "square," followed immediately by the left foot. The athlete continues this pattern along the length of the ladder. Upon reaching the end of the ladder, the athlete follows the same pattern described above but navigates the footwork backward in order to return to the starting position.

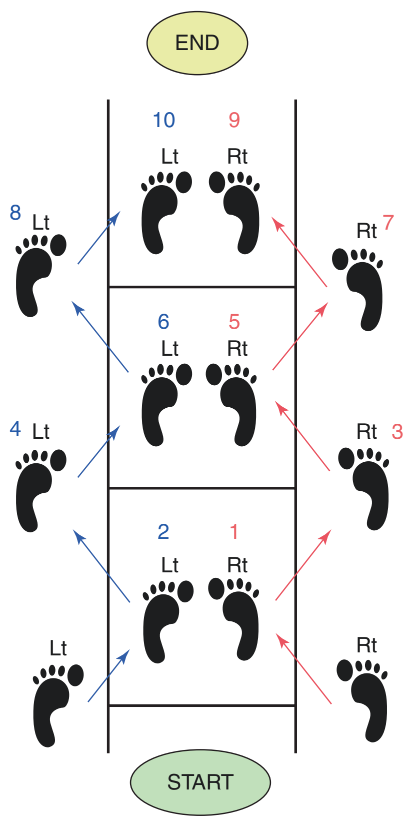


Fig. 17.14 Ladder: in-in, out-out. Only a portion of the 4.6 m ladder is shown for illustrative purposes [48]

17.3.3.5 Ladder: 1 Foot Forward, 1 Foot Backward

The athlete begins at the right end of the ladder and places the left foot inside the ladder and the right foot in front of the ladder (Fig. 17.15). The left foot is lifted slightly to step the right foot behind the ladder. Next, the left foot is stepped into the next square of the ladder to the left. The athlete repeats the pattern of placing the right foot in front of the ladder and then behind the ladder. Upon reaching the end of the ladder, the athlete switches legs so that the right foot is always in the ladder and the left foot steps to the front and to the back of the ladder.

17.3.3.6 Dot Drill: Double-Leg Jumps

For all of the dot drills, the athlete should be reminded to keep the knees and ankles aligned under their hips and the knees and toes pointed straight forward. The knees should be flexed at all times, and the landings should be soft and quiet. Avoid a valgus alignment and unstable (wiggle, wobble) knee position during takeoff and landing. For the double-leg jump, the athlete begins with both feet on A in the pattern shown in Fig. 17.16. The athlete jumps to B and then continues to C, D, E, C, and back to A.

17.3.3.7 Dot Drill: Split-Leg Jumps

The athlete performs the double-leg jump pattern, ending with both feet on C shown in Fig. 17.17. Then, the athlete immediately jumps and lands with the left foot on A and the right foot on B at the same time. The athlete jumps with both feet to C and then jumps with split feet to D and E. The athlete then returns back the same way without turning around.

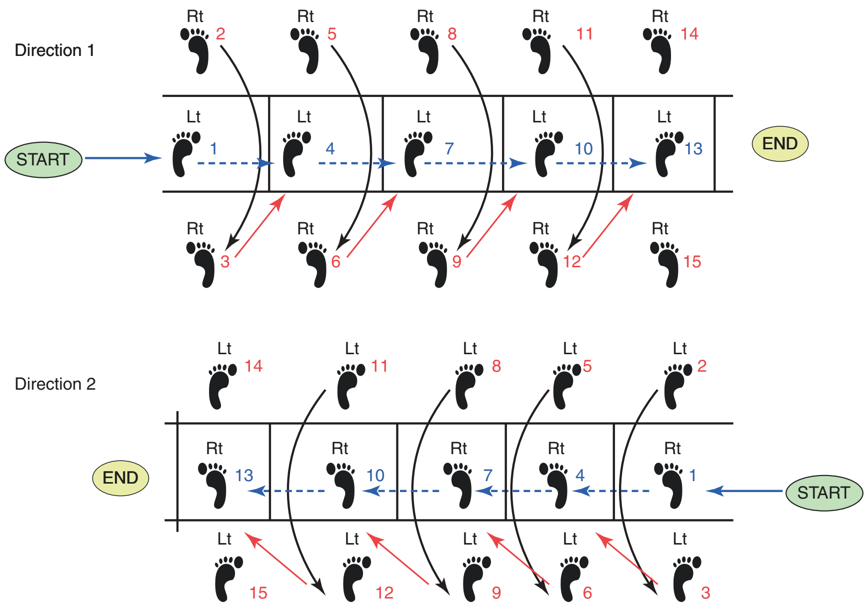


Fig. 17.15 Ladder: 1 foot forward, 1 foot backward. Only a portion of the 4.6-m ladder is shown for illustrative purposes [48]

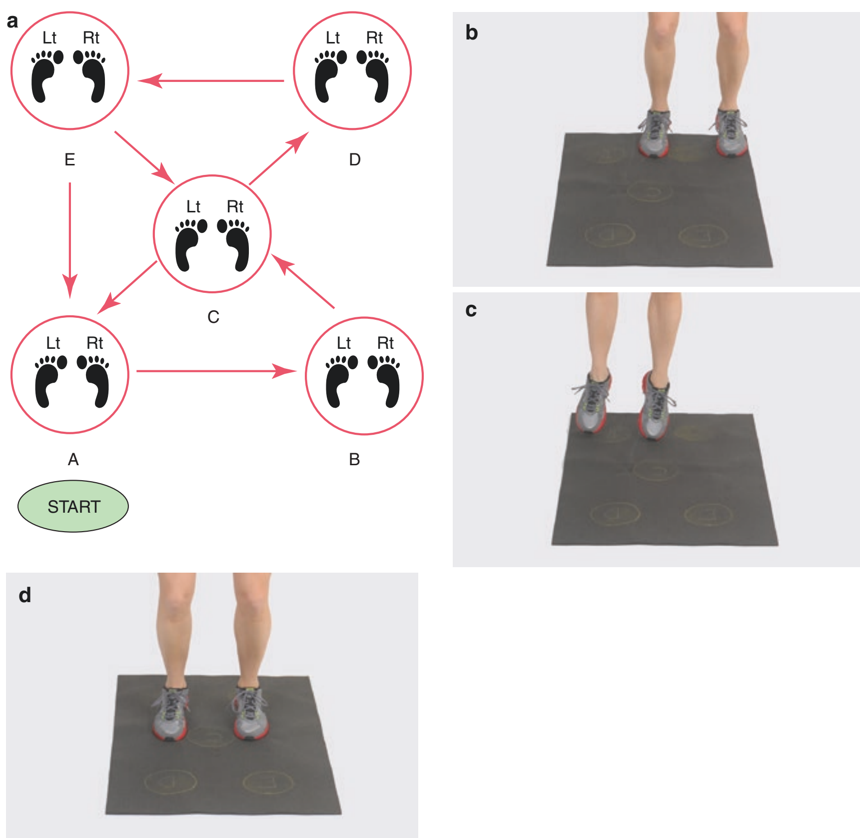


Fig. 17.16 Dot drills: double-leg jumps; (**a**) patterns and (**b**–**d**) directions [48]

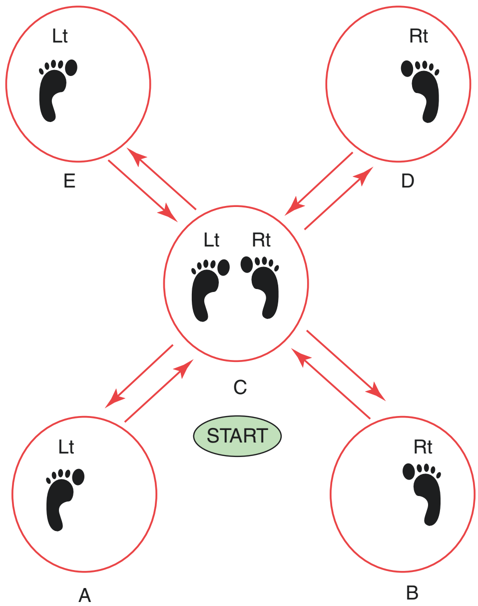


Fig. 17.17 Dot drills: split-leg jumps [48]

17.3.3.8 Dot Drill: 180° Split-Leg Jumps

The athlete performs the split-leg jumps, ending with the left foot on A and the right foot on B as shown in Fig. 17.18. The athlete jumps to C with both feet and then to D and E with split feet. The athlete quickly jumps, turns 180° to their left (facing the other direction), and lands with split feet on D and E. The athlete then jumps to C with both feet and then to A and B with split feet. The athlete turns quickly again with a 180° spin to the right and lands with split feet on A and B.

17.3.3.9 Dot Drill: Single-Leg Hops

The athlete performs the 180° split-leg jumps, ending with the left foot on A and the right foot on B. Then, the athlete jumps to C using only the right foot (Fig. 17.19). Using only the right foot, the athlete proceeds from D to E to C to A and to B. This pattern is repeated five times. Then, the

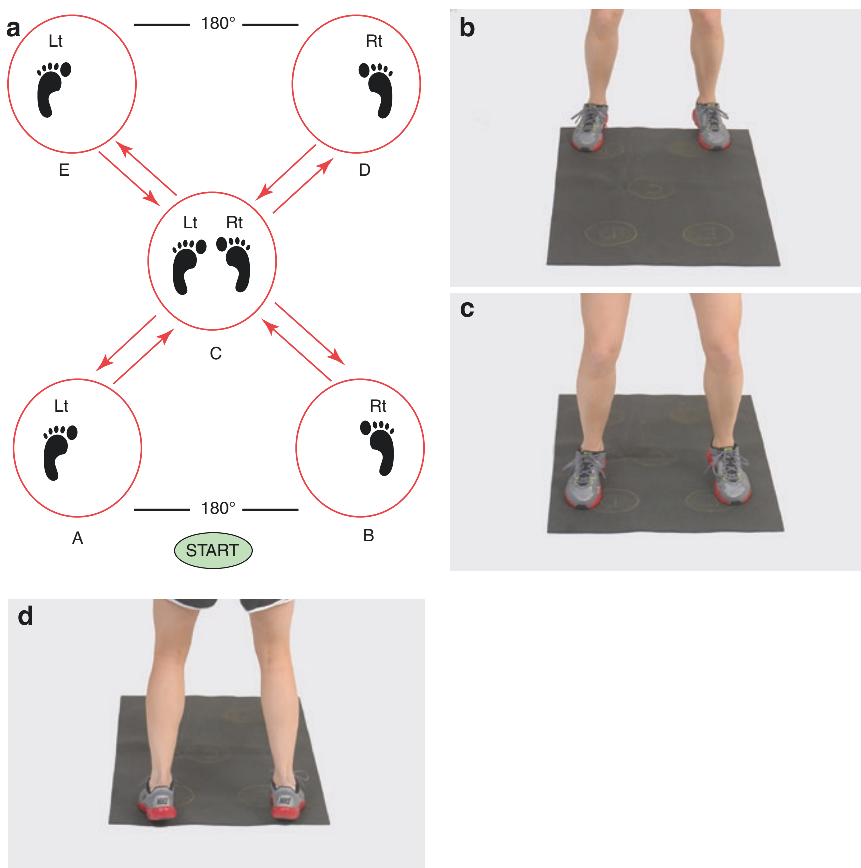


Fig. 17.18 Dot drills: 180° split-leg jumps; (**a**) patterns and (**b**–**d**) directions [48]

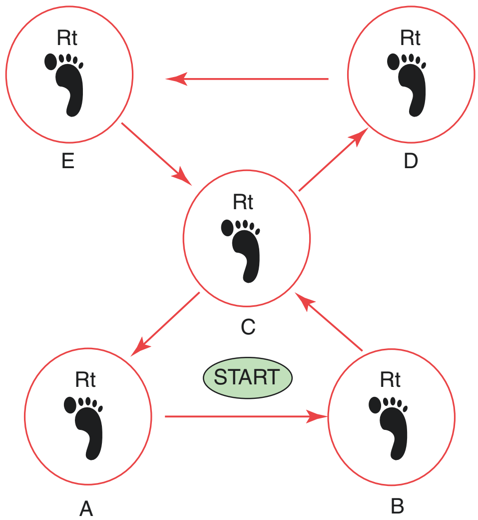


Fig. 17.19 Dot drills: single-leg hops [48]

athlete ends the last pattern on A and then jumps with the left foot only to B to C to D to E to C to A and to B.

17.3.3.10 Dot Drill: Combo All Jumps

Perform all four patterns as described above.

17.4 Basketball (Table 17.2)

17.4.1 Agility and Reaction Drills

17.4.1.1 Shuttle Drill

A course is set with six cones in a zigzag pattern within a 15 × 30 ft (4.6 × 27.4 m) area as shown in Fig. 17.20. Beginning at the first cone, the athlete sprints diagonally toward the second cone.

Table 17.2 Sportsmetrics Basketball training program[a]

Component	Session no.	Exercise	Duration
Agility, reaction	1–3	Shuttle drill	2 reps
	1–3	Maze drill	3 reps
	4–6	Tip drill	3 min
	4–6	Figure 4 drill	2 reps
	7–9	Square drill	2 reps
	7–9	4 dot drill, ¼ Eagles	3 reps
	10–12	Defensive slides	45 s, 3 reps
	10–12	Shoot and sprint	3 reps
	13–15	Tip drill	4 min
	13–15	Irish "D"	4 reps
	16–18	T-drill: 5–10-5	4 reps
	16–18	Kill the grass drill	2 min
Acceleration, speed, endurance	1–3	Mountain climbers	10 s, 5 reps
	1–3	Sprint-backpedal	5 reps
	1–3	Suicides	2 reps
	4–6	Mountain climbers	15 s, 5 reps
	4–6	Sprint-backpedal	7 reps
	4–6	Suicides: forward/ backward	2 reps
	7–9	Mountain climbers	20 s, 5 reps
	7–9	¼ Eagle sprint-backpedal	5 reps
	7–9	Suicides: defensive slides	2 reps
	10–12	Mountain climbers	25 s, 5 reps
	10–12	Sprint with ground touches	5 reps
	10–12	Full court relay	5 reps
	13–15	Mountain climbers	25 s, 5 reps
	13–15	Sprint-180°-backpedal	5 reps
	13–15	Sprint-quick feet	30 s, 2 reps
	16–18	Mountain climbers	30 s, 5 reps
	16–18	Sprint-360°-backpedal	5 reps
	16–18	Power rebounds relay	1 rep

(continued)

Table 17.2 (continued)

Component	Session no.	Exercise	Duration
Ladders, quick feet, additional jumps	1–3	Ladder: high knees	4 reps
	1–3	High knee ball toss over barrier	45 s, 2 reps
	1–3	Dot drill: double leg jumps	5 reps × 2
	4–6	Ladder: up-up, back-back	4 reps
	4–6	Double high knee with ball toss	2 reps
	4–6	Dot drill: add split leg jumps	5 reps × 2
	7–9	Ladder: outside foot in	4 reps
	7–9	Bleacher jumps	10 reps each leg × 2
	7–9	Dot drill: add 180° split leg jump	5 reps × 2
	10–12	Ladder: in-in, out-out	4 reps
	10–12	Instructor pointing	45 s, 2 reps
	10–12	Dot drills: add single-leg hops	5 reps × 3
	13–15	Ladder: scissors	4 reps
	13–15	Instructor pointing with quick feet up/down	45 s, 3 reps
	13–15	Dot drill: all jumps	5 reps × 3
	16–18	Ladder: Icky shuffle	4 reps
	16–18	Single-leg squat jumps and 180° scissor jumps	20 s each jump
	16–18	Dot drills: all jumps	5 reps × 3
Strength training, on the court	1–18	Squats with resistance band	Perform all exercises for 30 s during sessions 1–6, for 45 s during sessions 7–12, and for 60 s during sessions 13–18 Perform lower extremity exercises on Monday and Friday and upper extremity exercises on Wednesday
		Lunges with resistance band	
		Single-leg heel raises	
		Prone hamstring: hip extension with knee flexion	
		Supine hamstring bridge	
		Abdominals of choice	
		Hip flexion: steamboats	
		Hip abductor: lateral walk	
		Arm swing with resistance band	
		Internal rotation with resistance band with partner	
		External rotation with resistance band	
		Biceps curls with resistance band	
		Triceps extension with resistance band	
		Rows with resistance band	
		Push-ups	

[a]From Barber-Westin and Noyes [48]

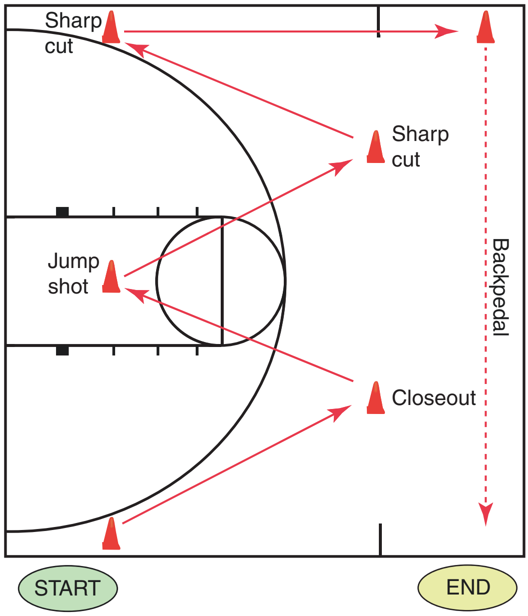


Fig. 17.20 Basketball shuttle drill. *Solid red lines* indicate forward sprints; *dotted line* indicates backpedaling [48]

Upon approaching the second cone, the athlete decelerates to allow for a defensive closeout. As soon as the closeout is performed, the athlete immediately accelerates to the third cone and performs a jump shot without a ball. Then, the athlete sprints to the fourth cone, decelerates, cuts around and touches the cone, and accelerates to the fifth cone. The athlete decelerates and performs a sharp cut around the fifth cone and sprints to the sixth cone where a 90° transition is done. The athlete then backpedals until the sideline is reached.

17.4.1.2 Maze Drill

Four cones are placed in a square formation within 12 ft (3.66 m), or the width of the lane, as shown in Fig. 17.21. The athlete begins behind the cone at the top of the key. Facing the backboard, the athlete slides horizontally to the far cone (along top of key). Upon reaching the cone, the athlete sprints toward the basket to the next cone and then slides horizontally to the far cone. Once the athlete reaches the last cone, they are tossed a ball to take an outside jump shot.

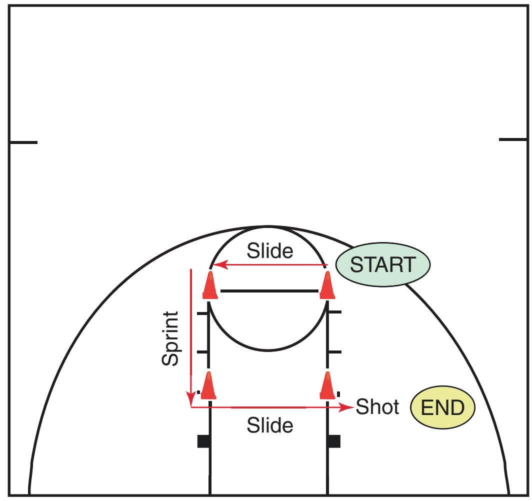


Fig. 17.21 Maze drill [48]

17.4.1.3 Tip Drill

The players are lined up so that one-half are facing one basket and the other half are facing the opposite basket. Each line has one ball. On signal, the first player in each line throws the ball up off of the backboard. The second player in line jumps up and tips it against the backboard, followed by the third player, and so on. After tipping the ball, each player must sprint to the opposite basket and fall in line until it is their turn to tip on that end. The drill continues as each athlete tips and sprints to the opposite basket. Each time the ball hits the floor, the clock is reset. The object is to go for the entire time without letting the ball hit the floor.

17.4.1.4 Figure 4 Drill

Four cones are arranged as shown in Fig. 17.22. The athlete begins on the baseline, positioned in the middle of the court. They sprint to half-court and touch the center court with both hands. The athlete slides backward to the sideline. Once the sideline is reached, the athlete slides across the court to the opposite sideline. As soon as the opposite sideline is reached, the athlete backpedals quickly to the baseline. Alternative moves may be considered. For instance, instead of backpedaling at the left-hand sideline, the athlete immediately grabs a jump rope and jumps for 30

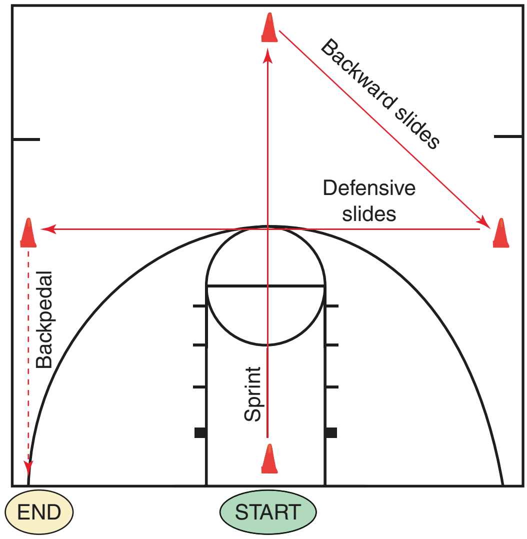


Fig. 17.22 Figure 4 drill [48]

repetitions before returning to the back of the line. Or, the athlete is tossed a ball for a jump shot if basketball hoops are located along the sidelines.

17.4.1.5 Square Drill

The athlete begins at the back corner of a large square as shown in Fig. 17.5. Moving around the outside of the square, the athlete sprints forward, slides laterally across, jumps up to a maximal vertical between each slide, backpedals to the backside, and slides laterally across the back of the square to the starting position. Then, the direction is reversed and the pattern repeated, starting with the lateral slide. Once the technique for this drill has been mastered, a ball may be incorporated. As the athlete moves laterally, the ball is passed to the athlete for a quick shot or a pass back to the instructor.

17.4.1.6 4 Dot Drill, Ladder

Place four cones in the shape of a square, 10 ft (3 m) apart, located to the side of the lane as shown in Fig. 17.23. Divide the athletes into two groups, one positioned at "start A" and the other at "start B." At start A, the athlete shuffles to the cone to the right, sprints forward to the next cone, and then shuffles to the cone to the left. Once this cone is reached, the athlete sprints 10–15 yards (9.1–13.7 m) straight ahead to a ladder where they perform the in-in/out-out ladder drill described in "Ladder: In-In, Out-Out." At the end of the ladder, the athlete shuffles to the right until they reach the 3-point line. At this point, the instructor passes a ball to the athlete where they attempt to make an outside shot. This athlete then gets in line for "start B." At start B, the athlete shuffles to the left, sprints forward, shuffles to the right, sprints forward through the ladders, and shuffles forward toward the free-throw line where an instructor passes the ball for a shot.

17.4.1.7 Defensive Slides

Place two cones approximately 15 ft (4.6 m) apart. The athlete may begin next to either cone. On the instructor's command, the athlete side shuffles from one cone to the other and back again. This pattern is repeated continuously and the athlete slaps the ground with their palms.

17.4.1.8 Shoot and Sprint

Using half the court, place one cone where the baseline and sideline meet on both sides and one cone at center court (Fig. 17.24). The athlete begins at the baseline cone on the left side and sprints to the cone at center court. The athlete sprints and touches the cone at center court and then sprints directly toward the basket. As the athlete approaches the free-throw line, they receive a ball from the instructor and continue on to shoot a layup. As soon as the athlete lands from the layup, they backpedal to center court and then sprint to the opposite corner from where they began. Once the entire group reaches the right side of the court, the drill is repeated in the exact same pattern but from the right side.

17.4.1.9 Irish D Drill

The athlete begins at the baseline, underneath the basket (Fig. 17.25) and performs five power jumps. The athlete then moves using defensive slides along the baseline to the 3-point line. They sprint from the 3-point line to the elbow and then perform defensive slides from the elbow to the middle of half-court. From half-court, the athlete sprints straight to the backboard. They perform five more power jumps under the backboard and

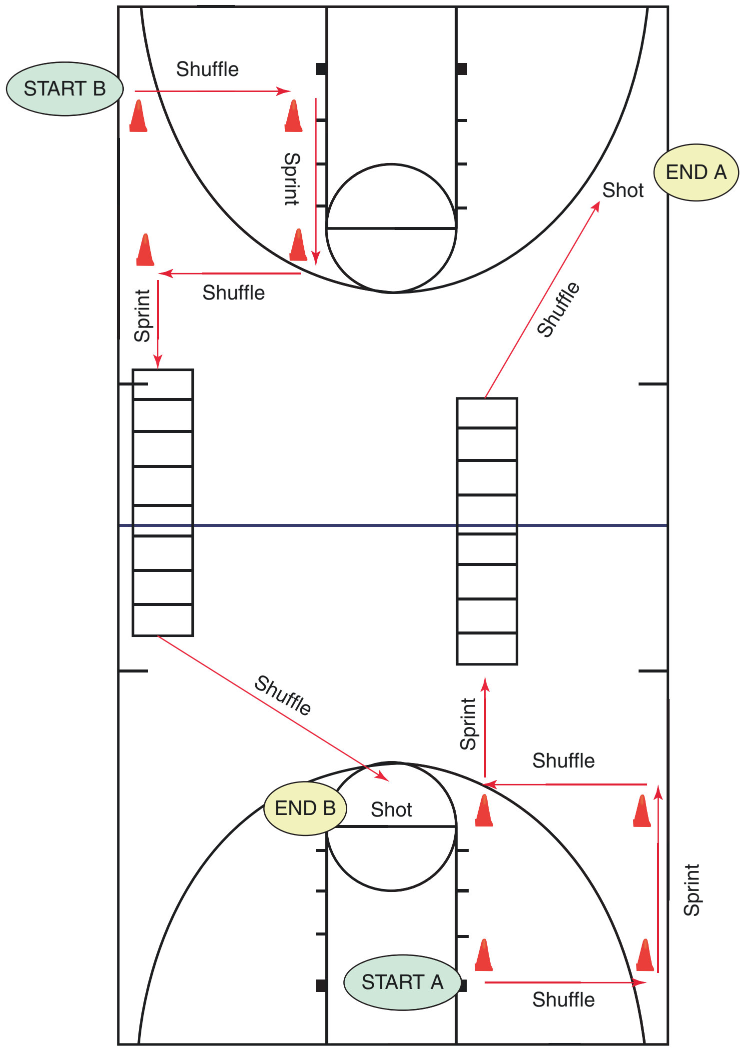


Fig. 17.23 4 dot drill, ladder [48]

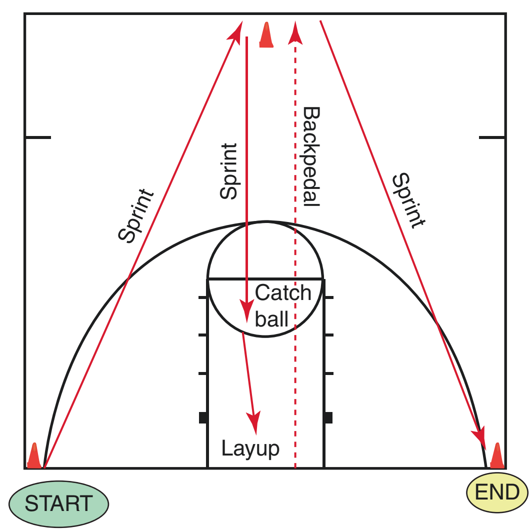


Fig. 17.24 Shoot and sprint drill [48]

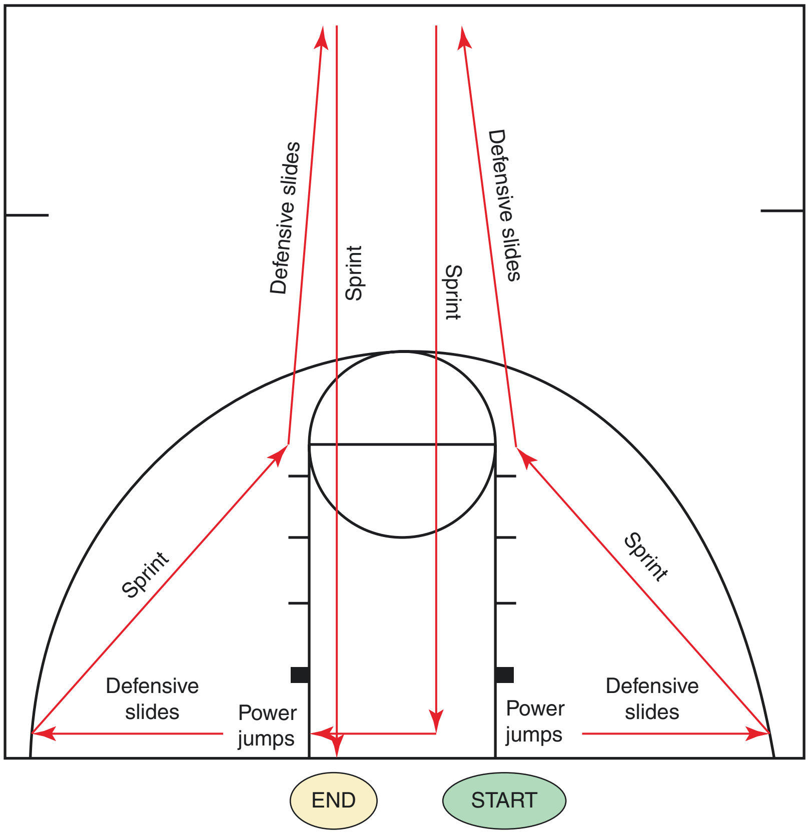


Fig. 17.25 Irish D drill [48]

then repeat the defensive slide/sprint pattern on the opposite side to complete one repetition.

17.4.1.10 T-Drill: 5–10-5

Three cones and a start/finish marker are arranged so that they form a capital letter "T" as shown in Fig. 17.8. Beginning at the base of the "T," the athlete sprints forward to the cone straight ahead. They tap the cone and slide left toward the cone to the left. The athlete taps the left-hand cone and slides to the right, past the middle cone, to the cone on the far right. They tap the right-hand cone and immediately take off in a sprint to the far left cone, tap that cone, sprint to the far right cone, tap that cone, sprint back to the far left cone, receive a pass from an instructor, and take a shot. After taking the shot, the athlete quickly returns to the back of the line for the next set.

17.4.1.11 Kill the Grass Drill

Five to ten players, each with a ball, are positioned inside the lane. The objective is for each player to move around the confined space while dribbling a basketball. The athletes should use both hands to dribble, change direction, and continuously move around. A variation of this drill is to have the athletes play knock out where each player tries to make the others lose control of the ball. Once a player loses their ball, they are eliminated. The game continues until there is only one player left. In order to increase the challenge, reduce the amount of space that the players are confined to as others are eliminated.

17.4.2 Acceleration, Speed, and Endurance Drills

17.4.2.1 Mountain Climbers

The athlete lines up on the baseline and faces half-court in proper push-up position. With palms planted on the ground, the right knee is driven up into the chest and then sprung back to its starting position while simultaneously driving the left knee up into the chest (Fig. 17.26) Alternate to the opposite leg in a quick motion and continue

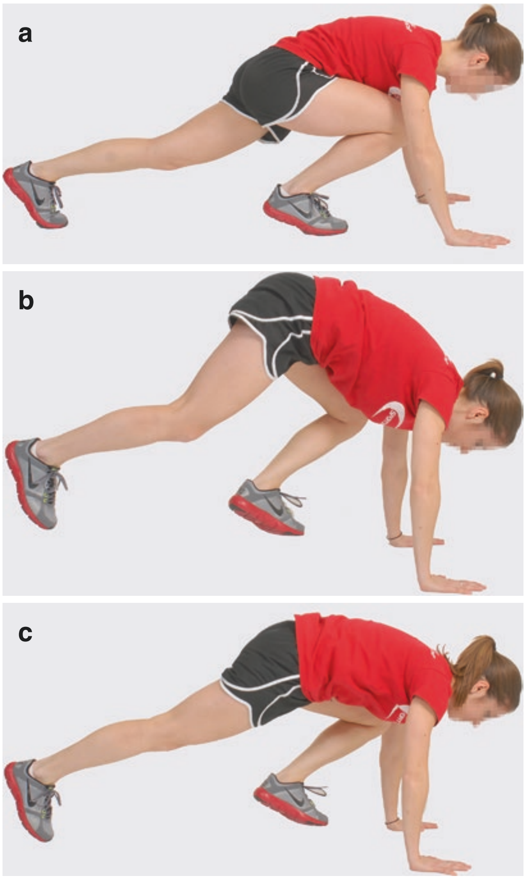


Fig. 17.26 Mountain climbers: (**a**) starting position, (**b**) leg switch, and (**c**) return to starting position [48]

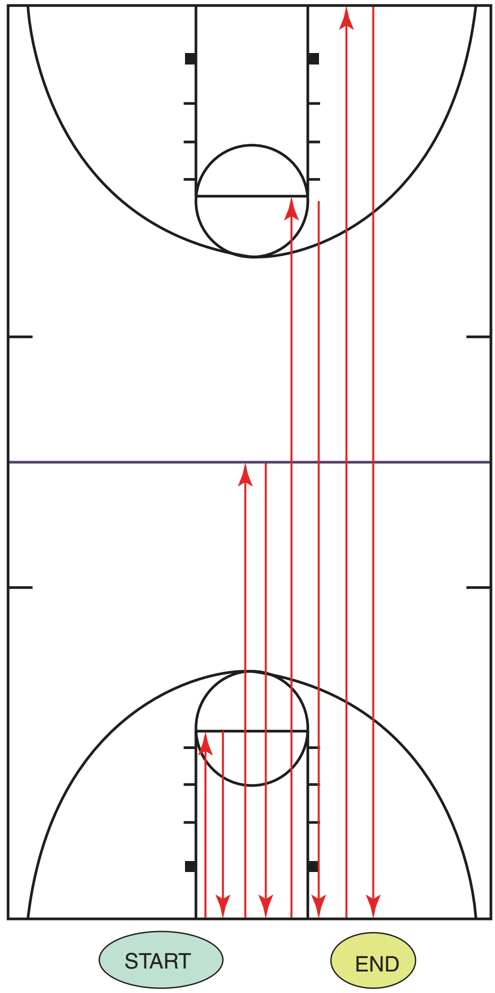


Fig. 17.27 Suicides on a basketball court. Run is done in a straight line; the figure depicts the eight segments individually for illustrative purposes only [48]

this process for a desired amount of time (usually 10–30 s). On the instructor's command, the athlete accelerates out of the mountain climber position and sprints to half-court. Then, the athlete jogs back to the baseline and returns to the mountain climber position; the next set begins on the instructor's command.

17.4.2.2 Sprint-Backpedal

Starting on the baseline of a standard basketball court, the athlete sprints forward to the baseline at the opposite end of the court. Upon reaching the opposite baseline, the athlete immediately backpedals at ¾ speed to the starting baseline.

17.4.2.3 Suicides

Starting on the baseline, the athlete sprints to the free-throw line and back to the baseline, to the half-court line and back to the baseline, to the far free-throw line and back to the baseline, and finally to the far baseline and back to the starting baseline (Fig. 17.27).

17.4.2.4 Suicides Forward-Backward

This is the same suicide drill as described above except the athlete sprints forward and always returns to the starting baseline by backpedaling.

17.4.2.5 ¼ Eagle Sprint-Backpedal

See section "¼ Eagle Sprint-Backpedal."

17.4.2.6 Suicides: Defensive Slides

This is the same suicide drill as described above except the athlete faces the sideline and performs defensive slides to the top of the free-throw line and back, to the half-court line and back, to the far free-throw line and back, and then to the far baseline and back.

17.4.2.7 Sprint with Ground Touches

The athlete begins on one baseline and sprints forward. Cones are positioned 15 yards (13.7 m) and 30 yards (27.4 m) away. The athlete must reach down quickly and, without stopping, touch the ground by the cone. The athlete should keep their feet positioned underneath the body while bending at the knees and hips to reach down. They immediately continue into a sprint until the opposite end of the court is reached, change direction, repeat the same ground touches, and return to the starting baseline.

17.4.2.8 Full-Court Relay

Split the athletes into even teams along the baseline. On the instructor's command, the first athlete from each team sprints forward to the opposite baseline and then backpedals back to the start. As the first team member crosses the baseline (starting baseline), the next team member begins to run. Continue this pattern until all of the athletes have run. The team who is first to have all of their players go and return to the baseline is the winner.

17.4.2.9 Sprint-180°-Backpedal

See section "Sprint-180°-Backpedal."

17.4.2.10 Sprint-Quick Feet-Backpedal

The players begin at the end line and sprint until the instructor commands "stop," at which time the athletes keep their feet moving quickly in the same spot until the instructor commands "go" and they then backpedal back to the end line again. Pattern is continued for amount of time desired.

17.4.2.11 Sprint-360°-Backpedal

The athlete begins at the baseline, sprints to the half-court line, and makes a 360° turn, keeping the feet and knees directly under the body and taking short, choppy steps. The athlete sprints to the opposite baseline and then backpedals to the starting position.

17.4.2.12 Power Rebounds Relay

The athletes are divided into even teams along the baseline. On the instructor's command, the first athlete from each team sprints forward to the foul line and then immediately backpedals back to the baseline and performs a power jump (Fig. 17.28). The athlete then sprints forward to half-court and immediately backpedals back to the baseline and performs a second power jump. Next, the athlete sprints forward to the top of the key (at the opposite end of the court) and then backpedals to the baseline and performs a

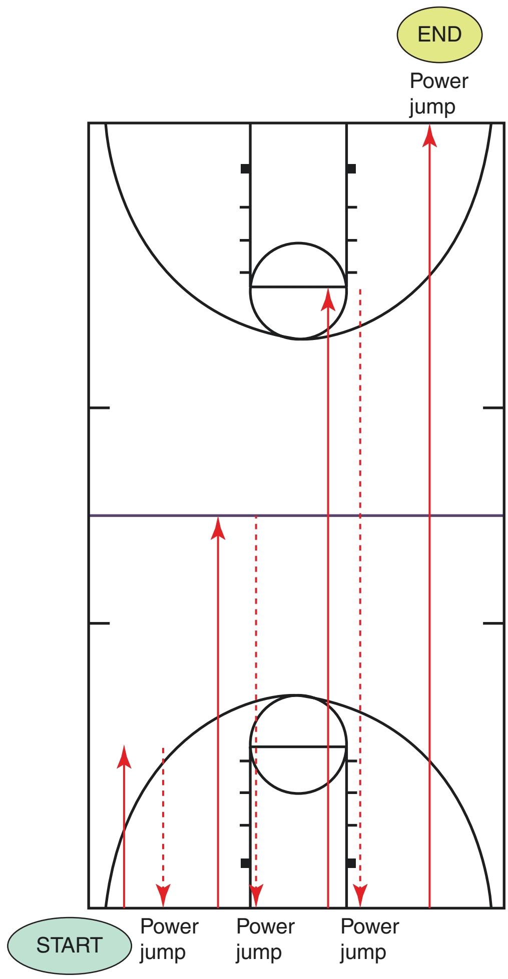


Fig. 17.28 Power rebounds relay. *Solid lines* indicate forward sprints; *dotted lines* indicate backpedaling [48]

third power jump. Finally, the athlete sprints full court to the opposite baseline and performs a fourth power jump. The final power jump acts as the signal for the next teammate to begin; the winner is the first team to have all of their members cross the opposite baseline.

17.4.3 Ladders, Quick Feet, Additional Jump Drills

17.4.3.1 Ladder: High Knees

The athlete begins behind the first ladder square and runs through the ladder sideways. Both feet should enter each square and the knees are driven up (around the height of the stomach). The athlete should try to lift their knees as quickly as possible and pump their arms in order to generate momentum (Fig. 17.29). The entire length of the ladder is traveled, and then the athlete immediately sprints forward (10–20 yards, 9.1–18.3 m) and jogs back to the starting position.

17.4.3.2 Ladder: Up-Up/Back-Back

See section "Ladder: Up-Up/Back-Back."

17.4.3.3 Ladder: Outside Foot In

See section "Ladder: Outside Foot In."

Fig. 17.29 Ladder: high knees from the (**a**) front and (**b**) side positions [48]

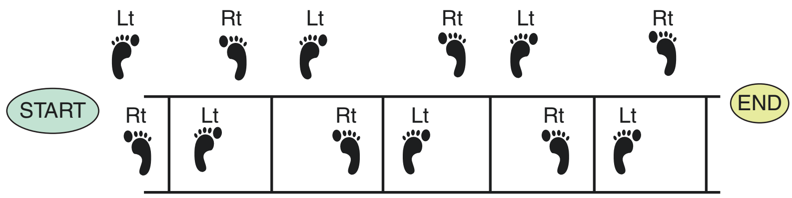


Fig. 17.30 Ladder: scissors. Only a portion of the ladder is shown for illustrative purposes [48]

17.4.3.4 Ladder: In-In, Out-Out

See section "Ladder: In-In, Out-Out."

17.4.3.5 Ladder: Scissors

The athlete begins at the left end of the ladder. They place the right foot inside the ladder and the left foot right in front of the ladder (Fig. 17.30). The athlete jumps up in the air, both feet leaving the ground at the same time, and scissor the legs so that the left foot lands inside the ladder and the right foot lands directly in front of the ladder at the same time. The athlete jumps up in the scissor motion again but lands in the second box to the right, so the right foot is again inside the ladder and the left foot is directly in front of the ladder. The athlete scissors once more in the second box so that the left foot lands inside the ladder and the right foot is in front of the ladder. This sequence is repeated as the athlete moves right from box to box along the ladder.

17.4.3.6 Ladder: Icky Shuffle

The athlete begins by stepping the right foot in the first box, followed by the left foot (Fig. 17.31). The athlete then steps the right foot up to the outside of the second box. Then the athlete steps the left foot directly into the second box and the right foot into the box next to the left foot. This pattern is repeated with the left foot leading the next step.

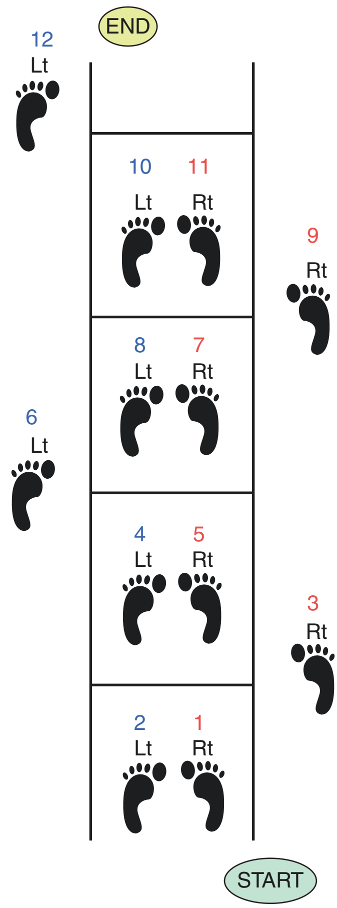


Fig. 17.31 Ladder: Icky shuffle. Only a portion of the ladder is shown for illustrative purposes [48]

17.4.3.7 High Knee Ball Toss Over Barrier

A barrier and partner are required for this drill. The athlete is positioned to the right of the barrier on the right leg, with the left knee drawn toward chest in a "Heisman" position (Fig. 17.32). The athlete jumps over the barrier off of the right foot and lands on the other side of the barrier on the left foot, with the right leg now drawn up toward chest in the "Heisman" position. Immediately upon landing, the partner gives a chest pass and the athlete must catch and pass the ball back before returning to the other side of the barrier. As soon as the athlete lands back on the right side on the right leg, the partner passes the ball again and the athlete passes it back. This pattern is continued back and forth over the barrier for 45 s.

Fig. 17.32 (**a**, **b**) High knee ball toss over barrier, "Heisman" position [48]

17.4.3.8 Double High Knee Ball Toss Over Barrier

This is the same drill as described above, except a second barrier is added. Between the "Heisman" poses and partner chest passes, the athlete performs high knees over both barriers.

17.4.3.9 Bleacher Jumps

Bleachers, plyometric boxes, or benches may be used to accomplish this drill. The athlete begins by facing the bleachers and places one foot on top of the bleacher so that the knee is flexed to 90°. In one powerful motion, the athlete thrusts straight up into the air by exploding off of the bleacher and then lands on the ground with both feet. Repeat this for a set amount of time (30–60 s) or for a specific amount of repetitions (10–20) and then switch to the opposite leg.

17.4.3.10 Single-Leg Squat Jumps

The single-leg squat jump is similar to the squat jump described in Chap. 17, except the athlete begins on one leg and squats as low to the ground as possible without allowing the knee to come forward over the toe or bending at the waist. Once the athlete has reached the lowest position in the squat, they jump straight up in the air as high as possible and land on the same leg, immediately going into a deep squat again.

17.4.3.11 180° Scissor Jumps

The 180° scissor jump is similar to the 180° jump described in Chap. 14. The athlete begins in a deep lunge position with the right foot forward. They jump straight up, turn 180° over the left shoulder, and land in a deep lunge position facing the opposite direction. Now the left foot should be forward. The jump is repeated, turning over the right shoulder.

17.4.3.12 Dot Drills

See sections "Dot Drill: Double-Leg Jumps, Dot Drill: Split-Leg Jumps, Dot Drill: 180° Split-Leg

Jumps, Dot Drill: Single-Leg Hops, and Dot Drill: Combo All Jumps."

17.5 Field Test Recommendations

17.5.1 Soccer Players

There are many field tests available for soccer players (Table 17.3) [56, 58–94]. The tests shown estimate maximal oxygen uptake and provide objective measurements of speed, agility, anaerobic power, dynamic balance and power, and strength. Normative values for several power, speed, agility, and aerobic fitness indices for soccer players are provided in Table 17.4 [57, 76, 95–97].

There have also been many cognitive, skill, and technique-based tests published for soccer [53–55, 57–59, 98–100]. In elite players, tests such as the Loughborough Soccer Passing Test and Loughborough Soccer Shooting Test may be used to determine their ability to perform multiple skills such as dribbling, passing, shooting, and sprinting [75]. However, these tests require extensive setup, instruction, and at least two examiners and may not be practical for high school athletes. Dribbling tests have been proposed and tested in male collegiate and competitive players. McGregor et al. [53, 101] developed the Loughborough Soccer Dribbling Test in which a player dribbles a ball between a line of six cones placed 3 m apart as fast as possible (Fig. 17.33). The amount of time taken to complete the test is recorded with a digital stopwatch. Ten tests are completed, with a 1-min rest period between each test. The sum of the times for all 10 trials is used as the final score. The validity coefficient is significant for this test ($R = 0.78$, $P < 0.01$).

Table 17.3 Field test recommendations for soccer players

Measure	Authors' recommended tests	Additional tests
Lower extremity strength, power, and dynamic balance	Countermovement vertical jump	Star Excursion Balance Test or Y-balance test
	Single-leg triple crossover hop	1-repetition maximum bench press
		1-repetition maximum leg press
		1-repetition maximum squat
		Squat jump
		Standing broad jump
Upper extremity power	Overhead toss with soccer ball	
Abdominal strength and endurance	Abdominal endurance test	
	60-s sit-up test	
Speed and agility	Pro agility test	*T* test
	10-m sprint	30-m sprint
	20-m sprint	Repeated sprints
		505 agility test
		Figure 8 agility test
		Illinois test
Aerobic fitness	Yo-Yo test level I or II	Multi-stage fitness test
Skill performance		Loughborough Soccer Dribbling Test [53]
		Haaland soccer dribble test [54]
		Johnson wall volley test [55]
		Lottermann agility/dribbling test [56]
		UGent dribbling test [57]
		Technical Skills Tests for Children and Youth, NFF, long pass and heading test [58]
		Star Challenge, UEFA, hit-the-post test [58]

NFF Football Association of Norway, *UEFA* European Football Association

Table 17.4 Sample normative mean values for soccer players

Study	Population description	Jumps (m)			Sprints (s)				Agility (s)			Aerobic (m)	
		CMV	Standing broad	Squat	5 m	10 m	20 m	30 m	Pro agility	*T* test	Illinois test	YY 1RT1	YY 1RT2
Lockie et al. [76]	All players; US female collegiate	0.51	1.94	NA	1.144	1.974	NA	4.719	5.090	NA	NA	1700	480
	Goalkeepers	0.54	2.07	NA	1.188	2.041	NA	4.864	4.935	NA	NA	980	240
	Defenders	0.48	2.01	NA	1.184	1.998	NA	4.688	5.140	NA	NA	2000	680
	Midfielders	0.51	1.92	NA	1.115	1.955	NA	4.754	5.105	NA	NA	1740	560
	Forwards	0.54	1.90	NA	1.148	1.986	NA	4.744	4.880	NA	NA	1400	440
McFarland et al. [95]	US female collegiate	0.42	NA	0.41	NA	1.92	NA	4.78	5.36	11.92	NA	NA	NA
	US male collegiate	0.58	NA	0.54	NA	1.63	NA	4.16	4.64	10.22	NA	NA	NA
Vandendriessche et al. [57]	Belgian national youth male U16	0.35	2.23	NA	1.072	1.817	3.133	4.380	NA	8.289	NA	NA	NA
	U16 futures	0.31	2.05	NA	1.096	1.905	3.288	4.630	NA	8.443	NA	NA	NA
	U17	0.36	2.30	NA	1.074	1.818	3.120	4.332	NA	8.147	NA	NA	NA
	U17 futures	0.32	2.11	NA	1.077	1.878	3.238	4.554	NA	8.237	NA	NA	NA
Gouvea et al. [96]	German national youth male U14	0.28	NA	0.28	NA	NA	NA	NA	NA	NA	NA	568	NA
	U17	0.32	NA	0.33	NA	NA	NA	NA	NA	NA	NA	878	NA
Vescovi et al. [97]	US high-level female aged 12–13	0.37	NA	NA	NA	NA	NA	NA	5.17	NA	10.80	NA	NA
	Aged 14–17	0.38	NA	NA	NA	NA	NA	NA	4.92	NA	10.36	NA	NA
	Aged 18–21	0.42	NA	NA	NA	NA	NA	NA	4.87	NA	10.20	NA	NA

CMV countermovement vertical, *YYIRT1* Yo-Yo intermittent recovery test level 1, *YYIRT2* Yo-Yo intermittent recovery test level 2

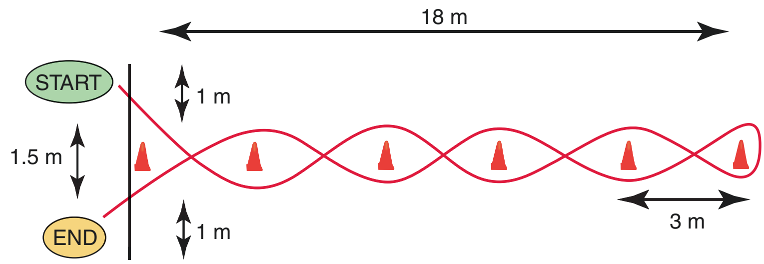


Fig. 17.33 Course for the Loughborough Soccer Dribbling Test [102]

Haaland et al. [54] described a similar dribbling test to that of McGregor; however, only five cones are used that are spaced 1 m apart. Subjects complete two tests on each leg, and the times are summed to produce a score (in s) for each leg. The coefficient of variation for this test is 4.3%. Vanderford et al. [55] described the Johnson wall volley test in which the player kicks a ball from a distance of 4.57 m into a regulation goal-sized target on a wall. The player then traps or kicks the ball on the rebound as many times as possible within a 30-s period. The athlete may kick the ball from the air or ground, but cannot use their arms or hands. Three tests are performed, with the sum of the number of kicks used to produce a score. Validity and reliability coefficients of 0.85 and 0.92, respectively, were previously established for this test [55].

17.5.2 Basketball Players

Table 17.5 shows the sports-specific field tests recommended for basketball players [25, 61, 64, 103–113]. The tests shown estimate maximal oxygen uptake and provide objective measurements of speed, agility, anaerobic power, dynamic balance and power, and strength. Normative values for several power, speed, agility, and aerobic fitness indices for basketball players are provided in Table 17.6 [25, 64, 103, 107, 108, 110].

Although several shooting and dribbling skill tests have been described, few have been rigorously validated [110, 114]. Pojskic et al. [110] evaluated the relationship between shooting performance and aerobic fitness, muscular strength, anaerobic endurance, and speed in elite male players (mean age, 18.97 ± 2.86). The investigators developed three tests of static (nonfatigued)

Table 17.5 Field test recommendations for basketball players

Measure	Authors' recommended tests	Additional tests
Lower extremity power and dynamic balance	Countermovement vertical jump	Star Excursion Balance Test
	Single-leg triple crossover hop	1-repetition maximum bench press
		1-repetition maximum leg press
		Squat jump
Upper extremity power	Overhead toss with soccer ball	Bench press
		60-s push-up test
		Closed kinetic chain upper extremity stability test
		Upper quarter Y-balance test
Abdominal strength and endurance	Abdominal endurance test	
	60-s sit-up test	
Upper extremity power	Chest pass (medicine ball or basketball)	
Speed and agility	Pro agility test	505 agility test
	T-test	V cut test
	20-m sprint	Illinois test
	10-m sprint	4 × 9 m suicide (shuttle) run
		Line drill test
Aerobic fitness	Yo-Yo test level I or II	Multi-stage fitness test
Skill performance		Speed shot shooting test
		Controlled dribble test
		Stationary free-throw shooting test
		Dynamic 60-s free-throw shooting test

Table 17.6 Sample normative mean values for basketball players

		Jumps (m)			Sprints (s)				Agility (s)			Aerobic		
Study	Population description	CMV	Standing broad	Squat	5 m	10 m	20 m	30 m	Pro agility	*T* test	Illinois test	YY 1RT1 (m)	YY 1RT2 (m)	MSFT (VO_{2max}: ml × kg^{-1} × min^{-1})
Asadi et al. [103]	Iranian elite male, mean age 19.7	0.49	224	NA	NA	NA	3.5	NA	NA	11.6	16.8	NA	NA	NA
Pojskic et al. [110]	Bosnian professional male, mean age 18.9	0.38	NA	0.31	NA	NA	3.14	NA	NA	10.48	NA	NA	NA	63.67
Ferioli et al. [107]	Italian male Division I	0.47	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Division II	0.49	NA	NA	NA	NA	NA	NA	NA	NA	NA	2135	NA	NA
	Division III	0.48	NA	NA	NA	NA	NA	NA	NA	NA	NA	2265	NA	NA
	Division IV	0.51	NA	NA	NA	NA	NA	NA	NA	NA	NA	1671	NA	NA
Arede et al. [25]	Spanish elite male Group 1, mean age 14.2	0.30	NA	0.27	NA	2.3	NA	NA	5.54	NA	NA	NA	NA	NA
	Group 2, mean age 14.9	0.29	NA	0.26	NA	2.0	NA	NA	5.68	NA	NA	NA	NA	NA
Gonzalo-Skok et al. [108]	Spanish elite U14	NA	NA	NA	1.135	1.919	3.352	NA	NA	NA	NA	NA	NA	NA
	U16	NA	NA	NA	1.082	1.835	3.159	NA	NA	NA	NA	NA	NA	NA
Delextrat and Cohen [64]	English elite National League Division II females, all players	0.42	NA	NA	NA	NA	3.50	NA	NA	10.45	NA	NA	NA	NA
	Guards	0.44	NA	NA	NA	NA	3.37	NA	NA	10.05	NA	NA	NA	NA
	Forwards	0.42	NA	NA	NA	NA	3.53	NA	NA	10.51	NA	NA	NA	NA
	Centers	0.40	NA	NA	NA	NA	3.59	NA	NA	10.74	NA	NA	NA	NA

and three tests of dynamic (fatigued) shooting performance. The tests included free throw, 2-point, and 3-point shots, with the dynamic analysis including sprinting between shots. All tests had adequate reliability (ICC, 0.81–0.92). Multiple correlations were found between the physical capacities and shooting performance, with stronger relationships found for the dynamic shooting tests. All three dynamic shooting tests also significantly correlated with real-game shooting statistics.

A speed-shot shooting test may be conducted as described by the American Alliance for Health, Physical Education, Recreation and Dance [114]. The gym floor is marked with five spots at a distance 4.5 m from the center of the backboard (Fig. 17.34). First, a 6-min warm-up is completed which consists of layups and spot-shooting with a partner. Then, over a 1-min period, the athlete shoots from each of the five spots at least once and as many times as possible. The athlete retrieves their own ball and dribbles to a subsequent spot. Four layup shots are allowed, but no two layups in succession. Each basket made equals 2 points and the total points are recorded. The ICC of this test is 0.95 for high school and 0.91 for collegiate female players. The results may be placed into percentile groups according to gender and age [114].

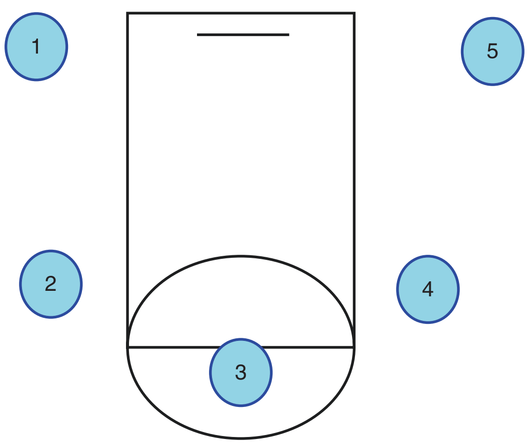


Fig. 17.34 Speed shot shooting test. Each spot numbered 1–5 is 4.5 m from the center of the backboard [102]

A second basketball test involves a controlled dribble [114]. An obstacle course is marked using six cones in the free-throw lane of the court (Fig. 17.35). The athlete starts on the non-dominant hand side of the first cone. On command, the athlete dribbles with the non-dominant hand to the non-dominant hand side of the second cone. The athlete proceeds to follow the course using the preferred hand, changing hands as required until crossing the finish line. The athlete may not travel or double-dribble and the ball must remain outside each cone. Two tests are completed and the sum of the scores is used for analysis. The results may be placed into percentile groups according to gender and age [114].

17.6 Results of Programs

17.6.1 Sportsmetrics Soccer

Our initial prospective study was conducted on 124 female soccer players aged 12 to 18 years [18], and updated data is shown in Table 17.7 for 294 soccer players aged 12 to 18. The training program resulted in significant increases in the mean absolute knee separation distance in the video drop-jump test ($P < 0.0001$, effect size [ES]

Fig. 17.35 Controlled dribble test course [102]

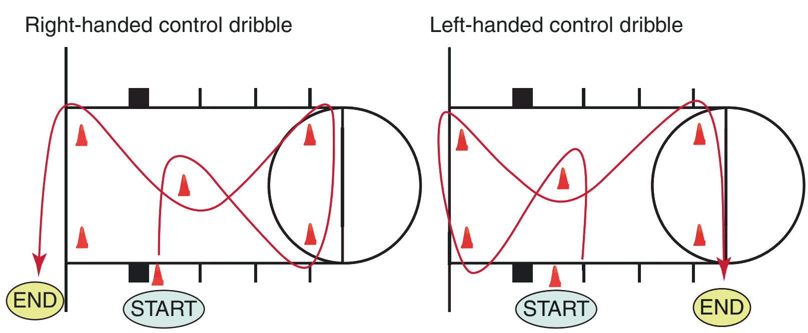


Table 17.7 Summary of effect of Sportsmetrics Soccer on athletic performance indices in 294 female soccer players aged 12–18

Test	Pre-train[a]	Post-train[a]	*P* value	Effect size
T test (s)	12.12 ± 1.17	11.43 ± 0.67	<0.0001	0.72
Drop-jump: normalized knee separation distance (%)	54 ± 22	67 ± 18	<0.0001	0.65
Multistage fitness test (ml kg^{-1} min^{-1})	38.1 ± 5.6	41.1 ± 5.4	<0.0001	0.54
60-s sit-up test (reps)	37.2 ± 8.1	40.8 ± 7.2	0.003	0.47
Single-leg triple hop, left leg (cm)	162.0 ± 20.4	167.5 ± 18.7	0.0003	0.28
Countermovement vertical jump (cm)	14.28 ± 2.75	14.98 ± 6.3	NS	NA
Single-leg triple hop, right leg (cm)	168.4 ± 18.3	172.0 ± 17.1	NS	NA
18-m sprint (s)	3.61 ± 0.32	3.95 ± 0.37	NS	NA

NA not applicable, *NS* not significant
[a]Data shown are mean ± SD

Table 17.8 Summary of effect of Sportsmetrics Basketball on athletic performance indices in female 322 basketball players aged 12–18

Test	Pre-train[a]	Post-train[a]	*P* value	Effect size
Drop-jump: normalized knee separation distance (%)	53 ± 19	71 ± 18	<0.0001	0.97
T test (s)	12.06 ± 0.79	11.42 ± 0.61	<0.0001	0.91
Multi-stage fitness test (ml kg^{-1} min^{-1})	35.0 ± 5.1	38.8 ± 5.9	<0.0001	0.69
60-s sit-up test (reps)	35.4 ± 8.7	38.3 ± 9.2	<0.0001	0.32
Countermovement vertical jump (cm)	14.66 ± 3.47	15.67 ± 6.7	0.01	0.19
Single-leg triple hop, left leg (cm)	145.0 ± 43.9	149.9 ± 44.96	NS	NA
Single-leg triple hop, right leg (cm)	148.2 ± 45.6	152.8 ± 46.4	NS	NA
18-m sprint (s)	3.62 ± 0.33	3.64 ± 0.31	NS	NA

NA not applicable, *NS* not significant
[a]Data shown are mean ± SD

0.65) indicating a more neutral lower limb alignment on landing. This finding is especially relevant in ACL-reconstructed knees, where a valgus lower limb position on landing would place the graft and/or the contralateral ACL at risk for rupture. Significant improvements were observed in the mean T-test agility score ($P < 0.0001$, ES 0.72), the multi-stage fitness test (MSFT) mean estimated maximal aerobic power (VO_2max) ($P < 0.0001$, ES 0.54), the mean repetitions performed in the 60-s sit-up test ($P = 0.003$, ES 0.47), and in the distance hopped in the single-leg triple hop test ($P = 0.0003$, ES 0.28). No subject sustained an injury that resulted in loss of time training or that required formal medical attention.

17.6.2 Sportsmetrics Basketball

Our initial prospective study was performed on 57 high school female basketball players aged 14–17 years [19], and updated data is shown in Table 17.8 for 322 basketball players aged 12–18. After training, significant increases were found in the mean absolute knee separation distance on the video drop-jump test ($P < 0.0001$, ES 0.97). Statistically significant improvements were also found in the mean *T* test score ($P < 0.0001$, ES 0.91), the mean estimated $V0_2max$ ($P < 0.0001$, ES 0.69), and in the mean repetitions in the 60-s sit-up test ($P < 0.0001$, ES 0.32). A significant improvement was found in the vertical jump test ($P = 0.01$). However, the effect size was small (0.19). No subject sustained an injury that resulted in loss of time training or that required formal medical attention.

References

1. Nielsen. 2018 World Football Report. The Nielsen Company. 2018. https://www.nielsen.com/uk/en/insights/reports/2018/world-football-report.html#. Accessed Jan. 16 2019
2. Clifton D, Onate J, Hertel J, Currie D, Knowles S, Pierpoint L, Wasserman E, Comstock R, Dompier T, Kerr Z. Descriptive Epidemiology of Injuries in US High School Girls' and NCAA Women's Basketball: 2004/05–2013/14. J Athl Train. 2017;52(6):S183.

3. DiStefano LJ, Dann CL, Chang CJ, Putukian M, Pierpoint LA, Currie DW, Knowles SB, Wasserman EB, Dompier TP, Comstock RD, Marshall SW, Kerr ZY. The first decade of web-based sports injury surveillance: descriptive epidemiology of injuries in US High School Girls' Soccer (2005–2006 Through 2013-2014) and National Collegiate Athletic Association Women's Soccer (2004–2005 Through 2013–2014). J Athl Train. 2018;53(9):880–92. https://doi.org/10.4085/1062-6050-156-17.
4. Kay MC, Register-Mihalik JK, Gray AD, Djoko A, Dompier TP, Kerr ZY. The epidemiology of severe injuries sustained by national collegiate athletic association student-athletes, 2009–2010 through 2014–2015. J Athl Train. 2017;52(2):117–28.
5. Kerr ZY, Lynall RC, Roos KG, Dalton SL, Djoko A, Dompier TP. Descriptive Epidemiology of Non-Time-Loss Injuries in Collegiate and High School Student-Athletes. J Athl Train. 2017;52(5):446–56. https://doi.org/10.4085/1062-6050-52.2.15.
6. Kuzuhara K, Shibata M, Uchida R. Injuries in Japanese junior soccer players during games and practices. J Athl Train. 2017;52(12):1147–52. https://doi.org/10.4085/1062-6050-52.12.23.
7. Mufty S, Bollars P, Vanlommel L, Van Crombrugge K, Corten K, Bellemans J. Injuries in male versus female soccer players: epidemiology of a nationwide study. Acta Orthop Belg. 2015;81(2):289–95.
8. Pfirrmann D, Herbst M, Ingelfinger P, Simon P, Tug S. Analysis of injury incidences in male professional adult and elite youth soccer players: a systematic review. J Athl Train. 2016;51(5):410–24. https://doi.org/10.4085/1062-6050-51.6.03.
9. Pierpoint LA, LaBella CR, Collins CL, Fields SK, Comstock RD. Injuries in girls' soccer and basketball: a comparison of high schools with and without athletic trainers. Inj Epidemiol. 2018;5(1):29.
10. Roos KG, Wasserman EB, Dalton SL, Gray A, Djoko A, Dompier TP, Kerr ZY. Epidemiology of 3825 injuries sustained in six seasons of National Collegiate Athletic Association men's and women's soccer (2009/2010–2014/2015). Br J Sports Med. 2017;51(13):1029–34. https://doi.org/10.1136/bjsports-2015-095718.
11. Zuckerman SL, Wegner AM, Roos KG, Djoko A, Dompier TP, Kerr ZY. Injuries sustained in National Collegiate Athletic Association men's and women's basketball, 2009/2010–2014/2015. Br J Sports Med. 2018;52(4):261–8.
12. Gans I, Retzky JS, Jones LC, Tanaka MJ. Epidemiology of recurrent anterior cruciate ligament injuries in National Collegiate Athletic Association Sports: The Injury Surveillance Program, 2004–2014. Orthop J Sports Med. 2018;6(6):2325967118777823. https://doi.org/10.1177/2325967118777823.
13. Joseph AM, Collins CL, Henke NM, Yard EE, Fields SK, Comstock RD. A multisport epidemiologic comparison of anterior cruciate ligament injuries in high school athletics. J Athl Train. 2013;48(6):810–7. https://doi.org/10.4085/1062-6050-48.6.03.
14. Stanley LE, Kerr ZY, Dompier TP, Padua DA. Sex differences in the incidence of anterior cruciate ligament, medial collateral ligament, and meniscal injuries in collegiate and high school sports: 2009–2010 through 2013–2014. Am J Sports Med. 2016;44(6):1565–72. https://doi.org/10.1177/0363546516630927.
15. Swenson DM, Collins CL, Best TM, Flanigan DC, Fields SK, Comstock RD. Epidemiology of knee injuries among U.S. high school athletes, 2005/2006–2010/2011. Med Sci Sports Exerc. 2013;45(3):462–9. https://doi.org/10.1249/MSS.0b013e318277acca.
16. Bizzini M, Hancock D, Impellizzeri F. Suggestions from the field for return to sports participation following anterior cruciate ligament reconstruction: soccer. J Orthop Sports Phys Ther. 2012;42(4):304–12. https://doi.org/10.2519/jospt.2012.4005.
17. Waters E. Suggestions from the field for return to sports participation following anterior cruciate ligament reconstruction: basketball. J Orthop Sports Phys Ther. 2012;42(4):326–36. https://doi.org/10.2519/jospt.2012.4030.
18. Noyes FR, Barber-Westin SD, Tutalo Smith ST, Campbell T. A training program to improve neuromuscular and performance indices in female high school soccer players. J Strength Cond Res. 2013;27(2):340–51. https://doi.org/10.1519/JSC.0b013e31825423d9.
19. Noyes FR, Barber-Westin SD, Smith ST, Campbell T, Garrison TT. A training program to improve neuromuscular and performance indices in female high school basketball players. J Strength Cond Res. 2012;26(3):709–19. https://doi.org/10.1519/JSC.0b013e318228194c.
20. Heckmann TP, Barber-Westin SD, Noyes FR. Rehabilitation of medial ligament injuries. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 636–52. https://doi.org/10.1016/b978-0-323-32903-3.00020-2.
21. Heckmann TP, Noyes FR, Barber-Westin SD. Rehabilitation of meniscus repair and transplantation procedures. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 760–71. https://doi.org/10.1016/b978-0-323-32903-3.00025-1.
22. Noyes FR, Barber-Westin SD, Heckmann TP. Rehabilitation of posterior cruciate ligament and posterolateral reconstructive procedures. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 578–606. https://doi.org/10.1016/b978-0-323-32903-3.00018-4.
23. Noyes FR, Heckmann TP, Barber-Westin SD. Rehabilitation after tibial and femoral osteotomy. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 858–867.e851. https://doi.org/10.1016/b978-0-323-32903-3.00028-7.

24. Noyes FR, Barber-Westin SD. Operative options for extensor mechanism malalignment and patellar dislocation. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 970–1013. https://doi.org/10.1016/b978-0-323-32903-3.00035-4.
25. Arede J, Vaz R, Franceschi A, Gonzalo-Skok O, Leite N. Effects of a combined strength and conditioning training program on physical abilities in adolescent male basketball players. J Sports Med Phys Fitness. 2018; https://doi.org/10.23736/s0022-4707.18.08961-2.
26. Beato M, Bianchi M, Coratella G, Merlini M, Drust B. Effects of plyometric and directional training on speed and jump performance in elite youth soccer players. J Strength Cond Res. 2018;32(2):289–96. https://doi.org/10.1519/JSC.0000000000002371.
27. Chaalali A, Rouissi M, Chtara M, Owen A, Bragazzi N, Moalla W, Chaouachi A, Amri M, Chamari K. Agility training in young elite soccer players: promising results compared to change of direction drills. Biol Sport. 2016;33(4):345–51.
28. Delextrat A, Gruet M, Bieuzen F. Effects of small-sided games and high-intensity interval training on aerobic and repeated sprint performance and peripheral muscle oxygenation changes in elite junior basketball players. J Strength Cond Res. 2018;32(7):1882–91. https://doi.org/10.1519/JSC.0000000000002570.
29. de Hoyo M, Gonzalo-Skok O, Sanudo B, Carrascal C, Plaza-Armas JR, Camacho-Candil F, Otero-Esquina C. Comparative effects of in-season full-back squat, resisted sprint training, and plyometric training on explosive performance in U-19 elite soccer players. J Strength Cond Res. 2016;30(2):368–77. https://doi.org/10.1519/JSC.0000000000001094.
30. Gonzalo-Skok O, Tous-Fajardo J, Arjol-Serrano JL, Suarez-Arrones L, Casajús JA, Mendez-Villanueva A. Improvement of repeated-sprint ability and horizontal-jumping performance in elite young basketball players with low-volume repeated-maximal-power training. Int J Sports Physiol Perform. 2016;11(4):464–73.
31. Jovanovic M, Sporis G, Omrcen D, Fiorentini F. Effects of speed, agility, quickness training method on power performance in elite soccer players. J Strength Cond Res. 2011;25(5):1285–92. https://doi.org/10.1519/JSC.0b013e3181d67c65.
32. Loturco I, Pereira LA, Kobal R, Maldonado T, Piazzi AF, Bottino A, Kitamura K, Cal Abad CC, de Arruda M, Nakamura FY. Improving sprint performance in soccer: effectiveness of jump squat and olympic push press exercises. PLoS One. 2016;11(4):e0153958. https://doi.org/10.1371/journal.pone.0153958.
33. Prieske O, Muehlbauer T, Borde R, Gube M, Bruhn S, Behm DG, Granacher U. Neuromuscular and athletic performance following core strength training in elite youth soccer: Role of instability. Scand J Med Sci Sports. 2016;26(1):48–56. https://doi.org/10.1111/sms.12403.
34. Ramírez-Campillo R, Vergara-Pedreros M, Henríquez-Olguín C, Martínez-Salazar C, Alvarez C, Nakamura FY, De La Fuente CI, Caniuqueo A, Alonso-Martinez AM, Izquierdo M. Effects of plyometric training on maximal-intensity exercise and endurance in male and female soccer players. J Sports Sci. 2016;34(8):687–93.
35. Rodriguez-Rosell D, Torres-Torrelo J, Franco-Marquez F, Gonzalez-Suarez JM, Gonzalez-Badillo JJ. Effects of light-load maximal lifting velocity weight training vs. combined weight training and plyometrics on sprint, vertical jump and strength performance in adult soccer players. J Sci Med Sport. 2017;20(7):695–9. https://doi.org/10.1016/j.jsams.2016.11.010.
36. Sanchez-Sanchez J, Carretero M, Ramirez-Campillo R, Petisco C, Diego M, Gonzalo-Skok O, Nakamura FYJK. Effects of high-intensity training with one versus three changes of direction on youth female basketball performance. Kinesiology. 2018;50(1):117–25.
37. Sedano S, Matheu A, Redondo JC, Cuadrado G. Effects of plyometric training on explosive strength, acceleration capacity and kicking speed in young elite soccer players. J Sports Med Phys Fitness. 2011;51(1):50–8.
38. Schelling X, Torres-Ronda L. Conditioning for basketball: quality and quantity of training. J Strength Cond Res. 2013;35(6):89–94.
39. Styles WJ, Matthews MJ, Comfort P. Effects of strength training on squat and sprint performance in soccer players. J Strength Cond Res. 2016;30(6):1534–9. https://doi.org/10.1519/jsc.0000000000001243.
40. Suarez-Arrones L, Saez de Villarreal E, Nunez FJ, Di Salvo V, Petri C, Buccolini A, Maldonado RA, Torreno N, Mendez-Villanueva A. In-season eccentric-overload training in elite soccer players: effects on body composition, strength and sprint performance. PLoS One. 2018;13(10):e0205332. https://doi.org/10.1371/journal.pone.0205332.
41. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lazaro-Haro C, Cugat R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: mechanisms of injury and underlying risk factors. Knee Surg Sports Traumatol Arthrosc. 2009;17(7):705–29. https://doi.org/10.1007/s00167-009-0813-1.
42. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engebretsen L, Bahr R, Krosshaug T. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. Am J Sports Med. 2010;38(11):2218–25. https://doi.org/10.1177/0363546510373570.
43. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lazaro-Haro C, Cugat R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. Knee Surg Sports Traumatol Arthrosc.

2009;17(8):859–79. https://doi.org/10.1007/s00167-009-0823-z.
44. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ, Russo KA. The effect of technique change on knee loads during sidestep cutting. Med Sci Sports Exerc. 2007;39(10):1765–73. https://doi.org/10.1249/mss.0b013e31812f56d1.
45. McNair PJ, Prapavessis H, Callender K. Decreasing landing forces: effect of instruction. Br J Sports Med. 2000;34(4):293–6.
46. Onate JA, Guskiewicz KM, Sullivan RJ. Augmented feedback reduces jump landing forces. J Orthop Sports Phys Ther. 2001;31(9):511–7.
47. Onate JA, Guskiewicz KM, Marshall SW, Giuliani C, Yu B, Garrett WE. Instruction of jump-landing technique using videotape feedback: altering lower extremity motion patterns. Am J Sports Med. 2005;33(6):831–42.
48. Barber-Westin S, Noyes FR. Sports-specific programs for soccer, basketball, volleyball, and tennis. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete. 2nd ed. Berlin Heidelberg, New York: Springer-Verlag; 2018. p. 377–425. https://doi.org/10.1007/978-3-662-56558-2_18.
49. Wilderman DR, Ross SE, Padua DA. Thigh muscle activity, knee motion, and impact force during side-step pivoting in agility-trained female basketball players. J Athl Train. 2009;44(1):14–25.
50. Zebis MK, Bencke J, Andersen LL, Dossing S, Alkjaer T, Magnusson SP, Kjaer M, Aagaard P. The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. Clin J Sport Med. 2008;18(4):329–37. https://doi.org/10.1097/JSM.0b013e31817f3e35.
51. Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, Kirkendall DT, Garrett W Jr. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med. 2005;33(7):1003–10. https://doi.org/10.1177/0363546504272261.
52. Foran B. High-performance sports conditioning. Champaign: Human Kinetics; 2001.
53. McGregor SJ, Nicholas CW, Lakomy HK, Williams C. The influence of intermittent high-intensity shuttle running and fluid ingestion on the performance of a soccer skill. J Sports Sci. 1999;17(11):895–903.
54. Haaland E, Hoff J. Non-dominant leg training improves the bilateral motor performance of soccer players. Scand J Med Sci Sports. 2003;13(3):179–84.
55. Vanderford ML, Meyers MC, Skelly WA, Stewart CC, Hamilton KL. Physiological and sport-specific skill response of olympic youth soccer athletes. J Strength Cond Res. 2004;18(2):334–42. https://doi.org/10.1519/R-11922.1.R-11922.
56. Honer O, Votteler A, Schmid M, Schultz F, Roth K. Psychometric properties of the motor diagnostics in the German football talent identification and development programme. J Sports Sci. 2015;33(2):145–59. https://doi.org/10.1080/02640414.2014.928416.
57. Vandendriessche JB, Vaeyens R, Vandorpe B, Lenoir M, Lefevre J, Philippaerts RM. Biological maturation, morphology, fitness, and motor coordination as part of a selection strategy in the search for international youth soccer players (age 15–16 years). J Sports Sci. 2012;30(15):1695–703. https://doi.org/10.1080/02640414.2011.652654.
58. Pedersen AV, Loras H, Norvang OP, Asplund J. Measuring soccer technique with easy-to-administer field tasks in female soccer players from four different competitive levels. Percept Mot Skills. 2014;119(3):961–70. https://doi.org/10.2466/03.30.PMS.119c31z2.
59. Ali A. Measuring soccer skill performance: a review. Scand J Med Sci Sports. 2011;21(2):170–83. https://doi.org/10.1111/j.1600-0838.2010.01256.x.
60. Aquino R, Palucci Vieira LH, de Paula Oliveira L, Cruz Goncalves LG, Pereira Santiago PR. Relationship between field tests and match running performance in high-level young Brazilian soccer players. J Sports Med Phys Fitness. 2018;58(3):256–62. https://doi.org/10.23736/s0022-4707.17.06651-8.
61. Ben Abdelkrim N, Castagna C, Jabri I, Battikh T, El Fazaa S, El Ati J. Activity profile and physiological requirements of junior elite basketball players in relation to aerobic-anaerobic fitness. J Strength Cond Res. 2010;24(9):2330–42. https://doi.org/10.1519/JSC.0b013e3181e381c1.
62. Chamari K, Chaouachi A, Hambli M, Kaouech F, Wisloff U, Castagna C. The five-jump test for distance as a field test to assess lower limb explosive power in soccer players. J Strength Cond Res. 2008;22(3):944–50. https://doi.org/10.1519/JSC.0b013e31816a57c6.
63. Delextrat A, Cohen D. Physiological testing of basketball players: toward a standard evaluation of anaerobic fitness. J Strength Cond Res. 2008;22(4):1066–72. https://doi.org/10.1519/JSC.0b013e3181739d9b.
64. Delextrat A, Cohen D. Strength, power, speed, and agility of women basketball players according to playing position. J Strength Cond Res. 2009;23(7):1974–81. https://doi.org/10.1519/JSC.0b013e3181b86a7e.
65. Deprez DN, Fransen J, Lenoir M, Philippaerts RM, Vaeyens R. A retrospective study on anthropometrical, physical fitness, and motor coordination characteristics that influence dropout, contract status, and first-team playing time in high-level soccer players aged eight to eighteen years. J Strength Cond Res. 2015;29(6):1692–704.
66. Dodd KD, Newans TJ. Talent identification for soccer: physiological aspects. J Sci Med Sport. 2018;21(10):1073–8. https://doi.org/10.1016/j.jsams.2018.01.009.
67. Drinkwater EJ, Pyne DB, McKenna MJ. Design and interpretation of anthropometric and fitness testing of basketball players. Sports Med (Auckland, NZ). 2008;38(7):565–78.
68. Eniseler N, Şahan Ç, Özcan I, Dinler K. High-intensity small-sided games versus repeated sprint training in junior soccer players. J Hum Kinet. 2017;60(1):101–11.

69. Francioni FM, Figueiredo AJ, Terribili M, Tessitore A. Analysis of the intraseasonal stability of field test performances in young academy soccer players. J Sports Sci. 2016;34(10):966–72.
70. Gabbett TJ, Sheppard JM, Pritchard-Peschek KR, Leveritt MD, Aldred MJ. Influence of closed skill and open skill warm-ups on the performance of speed, change of direction speed, vertical jump, and reactive agility in team sport athletes. J Strength Cond Res. 2008;22(5):1413–5. https://doi.org/10.1519/JSC.0b013e3181739ecd.
71. Granacher U, Prieske O, Majewski M, Büsch D, Mühlbauer T. The role of instability with plyometric training in sub-elite adolescent soccer players. Int J Sports Med. 2015;36(05):386–94.
72. Hetzler RK, Stickley CD, Lundquist KM, Kimura IF. Reliability and accuracy of handheld stopwatches compared with electronic timing in measuring sprint performance. J Strength Cond Res. 2008;22(6):1969–76. https://doi.org/10.1519/JSC.0b013e318185f36c.
73. Jones MT, Matthews TD, Murray M, Van Raalte J, Jensen BE. Psychological correlates of performance in female athletes during a 12-week off-season strength and conditioning program. J Strength Cond Res. 2010;24(3):619–28. https://doi.org/10.1519/JSC.0b013e3181cc23c3.
74. Kobal R, Loturco I, Gil S, Cal Abad CC, Cuniyochi R, Barroso R, Tricoli V. Comparison of physical performance among Brazilian elite soccer players of different age-categories. J Sports Med Phys Fitness. 2016;56(4):376–82.
75. Le Moal E, Rue O, Ajmol A, Abderrahman AB, Hammami MA, Ounis OB, Kebsi W, Zouhal H. Validation of the Loughborough Soccer Passing Test in young soccer players. J Strength Cond Res. 2014;28(5):1418–26. https://doi.org/10.1519/JSC.0000000000000296.
76. Lockie RG, Moreno MR, Lazar A, Orjalo AJ, Giuliano DV, Risso FG, Davis DL, Crelling JB, Lockwood JR, Jalilvand F. The physical and athletic performance characteristics of division I collegiate female soccer players by position. J Strength Cond Res. 2018;32(2):334–43. https://doi.org/10.1519/JSC.0000000000001561.
77. Lockie RG, Moreno MR, Orjalo AJ, Stage AA, Liu TM, Birmingham-Babauta SA, Hurley JM, Torne IA, Beiley MD, Risso FG, Davis DL, Lazar A, Stokes JJ, Giuliano DV. Repeated-sprint ability in division I collegiate male soccer players: positional differences and relationships with performance tests. J Strength Cond Res. 2017; https://doi.org/10.1519/JSC.0000000000001948.
78. Lockie RG, Jalilvand F, Moreno MR, Orjalo AJ, Risso FG, Nimphius S. Yo-Yo intermittent recovery test level 2 and its relationship with other typical soccer field tests in female collegiate soccer players. J Strength Cond Res. 2017;31(10):2667–77. https://doi.org/10.1519/JSC.0000000000001734.
79. Magal M, Smith RT, Dyer JJ, Hoffman JR. Seasonal variation in physical performance-related variables in male NCAA Division III soccer players. J Strength Cond Res. 2009;23(9):2555–9. https://doi.org/10.1519/JSC.0b013e3181b3ddbf.
80. Matlak J, Tihanyi J, Racz L. Relationship between reactive agility and change of direction speed in amateur soccer players. J Strength Cond Res. 2016;30(6):1547–52. https://doi.org/10.1519/jsc.0000000000001262.
81. Meckel Y, Machnai O, Eliakim A. Relationship among repeated sprint tests, aerobic fitness, and anaerobic fitness in elite adolescent soccer players. J Strength Cond Res. 2009;23(1):163–9. https://doi.org/10.1519/JSC.0b013e31818b9651.
82. Mirkov D, Nedeljkovic A, Kukolj M, Ugarkovic D, Jaric S. Evaluation of the reliability of soccer-specific field tests. J Strength Cond Res. 2008;22(4):1046–50. https://doi.org/10.1519/JSC.0b013e31816eb4af.
83. Myrick S. Injury prevention and performance enhancement: a training program for basketball. Conn Med. 2007;71(1):5–8.
84. Negra Y, Chaabene H, Hammami M, Amara S, Sammoud S, Mkaouer B, Hachana Y. Agility in young athletes: is it a different ability from speed and power? J Strength Cond Res. 2017;31(3):727–35. https://doi.org/10.1519/jsc.0000000000001543.
85. Paul DJ, Nassis GP. Testing strength and power in soccer players: the application of conventional and traditional methods of assessment. J Strength Cond Res. 2015;29(6):1748–58. https://doi.org/10.1519/jsc.0000000000000807.
86. Read PJ, Hughes J, Stewart P, Chavda S, Bishop C, Edwards M, Turner AN. A needs analysis and field-based testing battery for basketball. Strength Cond J. 2014;36(3):13–20. https://doi.org/10.1519/SSC.0000000000000051.
87. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. Phys Ther. 2007;87(3):337–49.
88. Reiman MP, Manske RC. Functional testing in human performance. Champaign: Human Kinetics; 2009.
89. Ribeiro YS, Balhego LL, Vecchio FBDJRBC, Humano D. Aerobic power and jumps predict performance in intermittent running test in young indoor soccer players. Rev Bras Cineantropom Desempenho Hum. 2015;17(3):357–66.
90. Rodriguez-Rosell D, Mora-Custodio R, Franco-Marquez F, Yanez-Garcia JM, Gonzalez-Badillo JJ. Traditional vs. sport-specific vertical jump tests: reliability, validity, and relationship with the legs strength and sprint performance in adult and teen soccer and basketball players. J Strength Cond Res. 2017;31(1):196–206. https://doi.org/10.1519/jsc.0000000000001476.
91. Rowat O, Fenner J, Unnithan V. Technical and physical determinants of soccer match-play performance in

elite youth soccer players. J Sports Med Phys Fitness. 2017;57(4):369–79.
92. Sassi RH, Dardouri W, Yahmed MH, Gmada N, Mahfoudhi ME, Gharbi Z. Relative and absolute reliability of a modified agility T-test and its relationship with vertical jump and straight sprint. J Strength Cond Res. 2009;23(6):1644–51. https://doi.org/10.1519/JSC.0b013e3181b425d2.
93. Vescovi JD, McGuigan MR. Relationships between sprinting, agility, and jump ability in female athletes. J Sports Sci. 2008;26(1):97–107. https://doi.org/10.1080/02640410701348644.
94. Ziv G, Lidor R. Vertical jump in female and male basketball players--a review of observational and experimental studies. J Sci Med Sport. 2010;13(3):332–9. https://doi.org/10.1016/j.jsams.2009.02.009.
95. McFarland IT, Dawes JJ, Elder CL, Lockie RG. Relationship of two vertical jumping tests to sprint and change of direction speed among male and female collegiate soccer players. Sports (Basel, Switzerland). 2016;4(1) https://doi.org/10.3390/sports4010011.
96. Gouvea M, Cyrino ES, Ribeiro AS, da Silva DR, Ohara D, Valente-Dos-Santos J, Coelho ESMJ, Ronque E. Influence of skeletal maturity on size, function and sport-specific technical skills in youth soccer players. Int J Sports Med. 2016;37(6):464–9. https://doi.org/10.1055/s-0035-1569370.
97. Vescovi JD, Rupf R, Brown TD, Marques MC. Physical performance characteristics of high-level female soccer players 12-21 years of age. Scand J Med Sci Sports. 2011;21(5):670–8. https://doi.org/10.1111/j.1600-0838.2009.01081.x.
98. Coratella G, Beato M, Schena F. The specificity of the Loughborough Intermittent Shuttle Test for recreational soccer players is independent of their intermittent running ability. Res in Spts Med. 2016;24(4):363–74.
99. Huijgen BC, Leemhuis S, Kok NM, Verburgh L, Oosterlaan J, Elferink-Gemser MT, Visscher C. Cognitive functions in elite and sub-elite youth soccer players aged 13 to 17 years. PLoS One. 2015;10(12):e0144580.
100. Vestberg T, Reinebo G, Maurex L, Ingvar M, Petrovic P. Core executive functions are associated with success in young elite soccer players. PLoS One. 2017;12(2):e0170845. https://doi.org/10.1371/journal.pone.0170845.
101. McGregor SJ, Hulse M, Strudwick A, Williams C. The reliability and validity of two tests of soccer skill. J Sports Sci. 1999;17:815.
102. Barber-Westin S, Noyes FR. Testing for neuromuscular problems and athletic performance. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete. 2nd ed. Berlin Heidelberg, New York: Springer-Verlag; 2018. p. 289–333. https://doi.org/10.1007/978-3-662-56558-2_16.
103. Asadi A, Arazi H. Relationship between test of postural control and strength and ability tests in basketball players. Rev Int de Cienc del Deporte. 2018;14(52) https://doi.org/10.5232/ricyde.
104. Carvalho HM, Goncalves CE, Grosgeorge B, Paes RR. Validity and usefulness of the Line Drill test for adolescent basketball players: a Bayesian multilevel analysis. Res Sports Med (Print). 2017;25(3):333–44. https://doi.org/10.1080/15438627.2017.1314296 .
105. Carvalho HM, Coelho e Silva MJ, Figueiredo AJ, GonÇalves CE, Castagna C, Philippaerts RM, Malina RM. Cross-validation and reliability of the Line-Drill Test of anaerobic performance in basketball players 14–16 years. J Strength Cond Res. 2011;25(4):1113–9.
106. Cronin JB, Owen GJ. Upper-body strength and power assessment in women using a chest pass. J Strength Cond Res. 2004;18(3):401–4. https://doi.org/10.1519/12072.1.
107. Ferioli D, Rampinini E, Bosio A, La Torre A, Azzolini M, Coutts AJ. The physical profile of adult male basketball players: differences between competitive levels and playing positions. J Sports Sci. 2018;36:1–8.
108. Gonzalo-Skok O, Serna J, Rhea MR, Marín PJ. Age differences in measures of functional movement and performance in highly trained youth basketball players. Int J Sports Phys Ther. 2017;12(5):812.
109. Oudejans RR. Effects of visual control training on the shooting performance of elite female basketball players. Int J Sports Sci Coach. 2012;7(3):469–80.
110. Pojskic H, Sisic N, Separovic V, Sekulic D. Association between conditioning capacities and shooting performance in professional basketball players: an analysis of stationary and dynamic shooting skills. J Strength Cond Res. 2018;32(7):1981–92.
111. Spiteri T, Nimphius S, Hart NH, Specos C, Sheppard JM, Newton RU. Contribution of strength characteristics to change of direction and agility performance in female basketball athletes. J Strength Cond Res. 2014;28(9):2415–23. https://doi.org/10.1519/JSC.0000000000000547.
112. Stojanović E, Aksović N, Stojiljković N, Stanković R, Scanlan AT, Milanović Z. Reliability, usefulness, and factorial validity of change-of-direction speed tests in adolescent basketball players. J Strength Cond Res. 2018; https://doi.org/10.1519/JSC.0000000000002666.
113. Taylor JB, Wright AA, Smoliga JM, DePew JT, Hegedus EJ. Upper-extremity physical-performance tests in college athletes. J Sport Rehab. 2016;25(2):146–54.
114. Hopkins DR, Shick J, Plack JJ. Basketball for boys and girls: skills test manual. Reston: Alliance for Health, Physical Education, Recreation and Dance; 1984. p. 18.

18 Return to Sport for Tennis

Sue Barber-Westin and Frank R. Noyes

18.1 Introduction

Tennis is a sport played by over 75 million participants worldwide [1] and is one of the few athletic activities that may be enjoyed well into mid-life. The elite adolescent player averages 2.3 h of practice or play per day a mean of 6.1 days a week. The average point requires 8.7 changes of direction, with each change creating a load of 1.5 to 2.7 times body weight on the lower extremity [2]. After the serve, a player runs an average of 3 m per shot, for a total of 8–15 m during one point, completing 1300–3600 m/h of play [3]. Players must be able to react quickly not only in a linear direction, but in multiple directions. During long and fast rallies, tennis elicits an average heart rate of 70–80% of maximum and can peak at 100% [3]. Mean oxygen uptake values are approximately 50–60% of maximum, with values reaching >80% during long rallies.

In the junior player, intense participation in tennis alone or in tennis combined with other sports significantly increases the risk of injury [4]. This is due to the heightened frequency, intensity, and duration of participation, along with the large biomechanical and physiological demands of competitive play. The most common injuries that occur during tennis involve the lower extremity and include muscle strains, meniscus tears, and ligament sprains [5–8].

In 2007, we developed a tennis-specific training program for competitive junior players, implementing the essential components of Sportsmetrics (see Chap. 14) along with other exercises designed to improve dynamic balance, agility, speed, and strength (Table 18.1). The program, called *Sportsmetrics Tennis*, offers a unique blend of neuromuscular retraining and sport-specific enhancement tasks to both improve player skill and aerobic fitness and decrease the risk of a lower extremity injury. The program entails 18 training session and is conducted three times a week for 6 weeks. We encourage all athletes who have suffered serious knee injuries, treated either conservatively or operatively, to complete this program as end-stage rehabilitation before resuming competitive tennis. In athletes who underwent ACL reconstruction, the rehabilitation principles and programs are detailed in Chaps. 11 and 14. Patients should have completed the running and agility program and the basic plyometric training program described in Chap. 14 before beginning Sportsmetrics Tennis. All of our postoperative rehabilitation programs for major knee operations are designed to restore strength, balance, proprioception, and neuromuscular indices required in athletes who wish to resume sports that require cutting, pivoting, twisting, turning,

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center,
The Noyes Knee Institute, Cincinnati, OH, USA

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_18

and landing [10–14]. Tennis involves all of these maneuvers in addition to linear, lateral, and multidirectional speed and agility.

A series of tests may be conducted before the first training session and after the final (18th) session to determine if further improvements are required in balance, agility, speed, or strength. We use the cost-effective field tests shown in Table 18.2. In addition, tests described by other investigators, along with normative data from elite players, are provided for the reader's benefit in Tables 18.3, 18.4, and 18.5 [3, 16, 27–29, 31–35].

Sportsmetrics Tennis begins with a 10-min dynamic warm-up to prepare the body for the physical demands of the sport, along with functional activities designed to raise core body temperature, increase heart rate, increase blood flow to the muscles and enhance flexibility, balance, and coordination. The dynamic warm-up and plyometric exercises are performed as described in Chap. 14. The program then moves to tennis-specific agility, speed, and aerobic conditioning drills. Static cool-down flexibility exercises are then performed as described in Chap. 14.

Sportsmetrics Tennis was conducted and validated in male and female junior players [21, 36] who participated in high school and mostly United States Tennis Association (USTA) Level

Table 18.1 Sportsmetrics tennis training program[a]

Component	Session no.	Exercise	Duration
Agility, reaction	1–3	Shadow swing baseline: forehand, backhand	2 sets × 10 reps each side
	1–3	Alternating short/deep balls: forehand, backhand	1 set × 10 reps each side
	4–6	Alternating short/deep balls: forehand, backhand	2 sets × 8 reps each side
	4–6	Resistance belt forehand, backhand	1 set × 10 reps each side
	7–9	Alternating short/deep balls: forehand, backhand	2 sets × 8 reps each side
	10–12	Rapid drop feed: forehand, backhand	2 sets × 8 reps each side
	13–15	Forehand, backhand reaction: facing net	2 sets × 8 reps each side
	13–15	Forehand, backhand reaction: facing fence	2 sets × 10 reps each side
	13–15	Rapid return serve feeds: forehand, backhand	2 sets × 8 reps each side
	16–18	Up-up, back-back, sprint to groundstroke, sprint to volley (forehand, backhand)	6 reps each side
Acceleration, speed, endurance	1–3	Suicides, 1-court	2 reps
	4–6	Net zigzag	2 reps
	4–6	Sprints	5 reps, baseline-net
	7–9	Forehand, backhand wide continuous hitting	8-6-6-8 reps
	7–12	Net zigzag	3 reps
	7–9	Suicides, 1-court	2 reps
	10–12	Baseline random feed: forehand, backhand	1 min, 2 min
	10–12	Sprint-quick feet-listen to instructor	3 min
	13–15	Suicides, 1-court	2 reps
	13–18	Suicides, 2-courts	1 rep
	13–15	Sprint-quick feet-listen to instructor	60 s, 3 reps
	16–18	Forehand, backhand wide continuous hitting	6-4-4-6 reps
	16–18	Suicides, 1-court	4 reps
Ladders, additional jumps	1–3	Up-up, back-back, sprint to cone, backpedal	2 reps
	4–6	Patterns 1 and 2	25 s each
	7–9	Up-up, back-back, sprint to cone, backpedal	3 reps
	7–9	Patterns 3 and 4	25 s each
	10–12	Patterns 5 and 6	25 s each
	13–15	Up-up, back-back, sprint to cone, backpedal	3 reps
	13–18	Backward broad jump	5–8 reps
	13–15	Patterns 7 and 8	25 s each
	16–18	Patterns 9 and 10	25 s each

Table 18.1 (continued)

Component	Session no.	Exercise	Duration
Strength training, on the court	1–6	Medicine ball forehand & backhand	2 sets × 8 reps
	10–12	Medicine ball forehand & backhand	2 sets × 12 reps
	1–3	Medicine ball overhead	2 sets × 8 reps
	4–6	Medicine ball backward, between legs	2 sets × 8 reps
	4–6	ETCH-swing forehand and backhand	1 set × 6 shots each side
	7–9	ETCH-swing forehand, backhand, serve	2 sets × 15 shots each side
	13–18	Medicine ball twisting lunges	2 sets × 8–10 reps
	1–18	Backward lunge, add hand weight day 4	1 full court × 2–4 reps
	1–3	Toe walking (full court)	Baseline – baseline × 2
	4–15	Toe walking (full court)	Baseline – baseline × 3
	16–18	Toe walking (full court)	Baseline – baseline × 4
	1–18	Regular or wall push-ups	Progress as desired
	1–18	Wall sits	3 sets × 45–80 s
	1–18	Wall sits, ball pressed between legs	3 sets × 45–90 s
	1–18	Abdominals, choose variety	150–500 reps
	1–3	TheraBand crab walking (1/2 court)	Baseline-net-baseline
	4–6	TheraBand crab walking (1/2 court)	Baseline-net-baseline ×2
	7–9	TheraBand crab jog, catch ball with partner (1/2 court)	Baseline-net-baseline ×2
	12–18	TheraBand crab jog, catch ball with partner (1/2 court)	Baseline-net-baseline ×3
	1–18	Tennis ball small circles	30–60 circles each arm, each direction
	1–18	Medicine ball overhead dribble	30–60 reps
	1–18	Medicine ball sideways core toss against wall	2 sets × 10–15 reps each side

s seconds
From Barber-Westin et al. [9]
[a]The dynamic warm-up, jump training, and flexibility exercises are described in Chap. 14

Table 18.2 Field tests for tennis players

Measure	Authors' recommended field tests	Tests described by other investigators
Lower extremity power and dynamic balance	Single-leg hop [15]	Countermovement vertical jump (contact mats) [16, 17]
	Single-leg triple crossover hop [15]	Isokinetic testing quadriceps and hamstrings (180°/s, 300°/s) [18]
	1-repetition maximum leg press	
	Countermovement vertical jump Vertec)	
Upper body strength and power	Sitting medicine ball chest pass [19]	Push-up test [17]
	Medicine ball toss: chest pass, forehand toss, backhand toss, overhead	Isokinetic testing trunk rotation [20]
	1-Repetition maximum bench press [21, 22]	Handgrip strength (handheld dynamometer) [16, 17]
		Serve velocity (radar gun) [3, 17]
Abdominal strength and endurance	Sit-up test	
	Abdominal endurance test [21]	
Speed and agility	1-Court suicide [21]	Tennis-specific sprint test (signal panel and 2 LEDs) [17]
	2-Court suicide [21]	Planned and reactive agility test (electronic timing system and light stimuli) [23]
	Baseline forehand and backhand tests [21]	
	Service box test [21]	
	10-m sprint	
	20-m sprint	
Aerobic fitness	Multistage fitness test [24, 25]	The Girard test (computer) [26]
	Yo-Yo test level 1 and level 2	The Hit and Turn Tennis test (CD player) [27]
		Test to Exhaustion Specific to Tennis (ball machine and radar gun) [28]
		The NAVTEN (CD player) [29]
		Repeated sprint ability shuttle test (light cells) [30]

CD compact disc, *LED* light-emitting diode, *NAVTEN* French for shuttle-tennis

Table 18.3 Sample mean values of aerobic endurance tests in elite tennis players

Study	Cohort details	Aerobic test				
		Hit and turn tennis test (estimated VO_2max)	Test to exhaustion specific to tennis (VO_2max)	MSFT (estimated VO_2max)	Yo-Yo intermittent recovery (m)	NAVTEN VO_2max (ml kg^{-1} min^{-1})
Ferrauti et al. [27]	*German tennis federation elite players*					
	U14 males	Level: 13.1 VO_2max: 55.0	NA	NA	NA	NA
	U16 males	Level: 14.4 VO_2max: 57.7	NA	NA	NA	NA
	U14 females	Level: 11.6 VO_2max: 50.4	NA	NA	NA	NA
	U16 females	Level: 11.7 VO_2max: 49.0	NA	NA	NA	NA
	Adult males	Level: 16.1 VO_2max: 60.4	NA	NA	NA	NA
	Adult females	Level: 11.8 VO_2max: 47.3	NA	NA	NA	NA
Ulbricht et al. [31]	*German tennis federation national squad*					
	U12 males	Level: 13.9	NA	NA	NA	NA
	U12 females	Level: 11.6	NA	NA	NA	NA
	U14 males	Level: 15.1	NA	NA	NA	NA
	U14 females	Level: 13.7	NA	NA	NA	NA
	U16 males	Level: 16.9	NA	NA	NA	NA
	U16 females	Level: 15.5	NA	NA	NA	NA
Fernandez-Fernandez et al. [3]	*German tennis federation elite players*					
	U12 males	Level: 12.4	NA	NA	NA	NA
	U12 females	Level: 12.7	NA	NA	NA	NA
	U14 males	Level: 14.1	NA	NA	NA	NA
	U14 females	Level: 12.7	NA	NA	NA	NA
	U16 males	Level: 16.3	NA	NA	NA	NA
	U16 females	Level: 13.8	NA	NA	NA	NA
	U18 males	Level: 17.7	NA	NA	NA	NA
	U18 females	Level: 14.3	NA	NA	NA	NA
Brechbuhl et al. [28]	*French tennis federation elite players, males & females*					
		NA	56.5	55.2	NA	NA
Fargeas-Gluck et al. [29]	*Regional elite players, mean age 12.9 years*					
		NA	NA	54.2	NA	54.9
Myburgh et al. [32]	*Great Britain nationally ranked players*					
	U10-12 males	NA	NA	NA	1336	NA
	U10-12 females	NA	NA	NA	1286	NA
	U13-16 males	NA	NA	NA	1736	NA
	U13-16 females	NA	NA	NA	1065	NA

NA not available, *VO_2max* (ml kg^{-1} min^{-1})

Table 18.4 Sample mean values of strength and power in elite tennis players

Study	Cohort details	Grip strength (kg)	CMJ (cm)	Medicine ball throws (m)		
				Overhead	Forehand	Backhand
Fernandez-Fernandez et al. [3]	*German tennis federation elite players*					
	U12 males	21.6	28.9	5.2	NA	NA
	U12 females	20.6	28.6	5.0	NA	NA
	U14 males	28.3	31.0	6.3	NA	NA
	U14 females	27.4	29.8	6.1	NA	NA
	U16 males	39.7	36.5	8.7	NA	NA
	U16 females	32.1	31.1	7.1	NA	NA
	U18 males	49.8	39.9	10.9	NA	NA
	U18 females	35.7	31.1	7.9	NA	NA
Ulbricht et al. [31]	*German tennis federation national players*					
	U12 males	24.1	29.8	5.7	7.3	7.0
	U12 females	23.2	27.9	5.2	6.8	6.5
	U14 males	28.6	32.7	7.1	9.3	8.9
	U14 females	29.0	30.1	6.6	8.6	8.3
	U16 males	42.9	36.9	9.7	12.5	12.1
	U16 females	35.5	31.7	7.5	9.8	9.4
Myburgh et al. [32]	*Great Britain nationally ranked players*					
	U10-12 males	23.9	39.0	7.9	10.6	9.9
	U10-12 females	23.8	40.3	7.2	10.0	9.3
	U13-16 males	40.0	50.2	11.7	15.9	15.6
	U13-16 females	34.1	41.9	10.0	12.7	12.1
Girard et al. [16]	*International tennis federation mean age 13.6 years*					
	Males	17.56	32.9	NA	NA	NA
Kramer et al. [33]	*Netherlands elite high ranked players*					
	U14 males	NA	30.6	9.6	NA	NA
	U14 females	NA	31.7	9.6	NA	NA
	U15 males	NA	31.9	10.7	NA	NA
	U15 females	NA	31.6	9.9	NA	NA
	U16 males	NA	36.0	12.5	NA	NA
	U16 females	NA	30.4	10.4	NA	NA
Kramer et al. [34]	*Dutch nationally ranked mean age 12.4 years*					
	Males	NA	30.6	9.30	NA	NA
	Females	NA	29.6	9.17	NA	NA
Munivrana et al. [35]	*Slovenian national junior teams*					
	U16 males	NA	51.63	NA	NA	NA
	U16 females	NA	43.3	NA	NA	NA
	U18 males	NA	53.3	NA	NA	NA
	U18 females	NA	43.0	NA	NA	NA

NA not available

Table 18.5 Sample mean values of speed and agility in strength and power elite tennis players

Study	Population	Sprints (s)				Agility (s)	
		5 m	10 m	15 m	20 m	Forehand	Backhand
Fernandez-Fernandez et al. [3]	*German tennis federation elite players*						
	U12 males	NA	2.04	NA	3.64	3.06	3.16
	U12 females	NA	2.03	NA	3.61	3.11	3.21
	U14 males	NA	1.96	NA	3.47	2.96	3.08
	U14 females	NA	1.98	NA	3.50	2.99	3.12
	U16 males	NA	1.85	NA	3.25	2.77	2.90
	U16 females	NA	1.96	NA	3.41	2.88	3.03
	U18 males	NA	1.77	NA	3.09	2.72	2.86
	U18 females	NA	1.96	NA	3.38	2.88	3.05
Ulbricht et al. [31]	*German tennis federation national players*						
	U12 males	NA	2.00	NA	3.52	NA	NA
	U12 females	NA	2.02	NA	3.60	NA	NA
	U14 males	NA	1.95	NA	3.45	NA	NA
	U14 females	NA	1.99	NA	3.50	NA	NA
	U16 males	NA	1.85	NA	3.22	NA	NA
	U16 females	NA	1.93	NA	3.38	NA	NA
Myburgh et al. [32]	*Great Britain nationally ranked players*						
	U10-12 males	1.20	2.06	NA	3.59	NA	NA
	U10-13 females	1.19	2.05	NA	3.60	NA	NA
	U13-16 males	1.06	1.85	NA	3.25	NA	NA
	U13-16 females	1.18	1.99	NA	3.47	NA	NA
Girard et al. [16]	*International tennis federation mean age 13.6 years*						
	Males	1.19	2.02	NA	3.55	NA	NA
Kramer et al. [33]	*Netherlands elite high ranked players*						
	U14 males	0.98	1.87	NA	NA	NA	NA
	U14 females	0.99	1.87	NA	NA	NA	NA
	U15 males	0.95	1.82	NA	NA	NA	NA
	U15 females	0.97	1.84	NA	NA	NA	NA
	U16 males	0.92	1.74	NA	NA	NA	NA
	U16 females	0.96	1.83	NA	NA	NA	NA
Kramer et al. [34]	*Dutch nationally ranked mean age 12.4 years*						
	Males	1.00	1.89	NA	NA	NA	NA
	Females	1.00	1.90	NA	NA	NA	NA
Munivrana et al. [35]	*Slovenian national junior teams*						
	U16 males	1.5	NA	NA	3.6	NA	NA
	U16 females	1.5	NA	NA	3.7	NA	NA
	U18 males	1.4	NA	NA	3.3	NA	NA
	U18 females	1.4	NA	NA	3.6	NA	NA

NA not available

6–7 tournament play [37]. For elite national and international players, further training is expected to be required to return to the highest level of competition. A variety of resources are available that describe training and conditioning concepts for these elite athletes [30, 38–49].

18.2 Techniques for Running, Agility, and Reaction Drills

Common playing situations noted at the time of anterior cruciate ligament (ACL) injury involve landing from a jump or a change of direction such as a cut or pivot, combined with deceleration where the knee is near full extension and the foot is firmly fixed flat on the playing surface [50, 51]. The center of mass of the body is often noted to be far from the area of foot-ground contact. Valgus collapse at the knee is frequently reported, although it is unknown whether this abnormal position occurs before, during, or just after the ACL rupture.

Rehabilitation and sport-specific training programs for patients recovering from ACL reconstruction or other major knee operations should include instruction to avoid at-risk situations during landing from a jump, decelerating, cutting, and pivoting maneuvers [52, 53]. The Sportsmetrics Tennis program described in this chapter involves a number of drills designed to familiarize and enhance the athletes' ability to perform planned as well as unanticipated changes of direction. Awareness training techniques including verbal and visual feedback are considered vital to successfully correct form for the most difficult athletic maneuvers. The combination of verbal cues from an expert instructor and feedback of videotape samples of the athlete performing a task has been shown to reduce impact loads and improve maximum knee flexion during jump-landing [54–56]. Recommended instructions for agility and reaction drills include the following (Fig. 18.1) [50, 53, 57–60]:

1. Regardless of the direction, the first step should be short. Keep the toes pointed forward.
2. Maintain, as much as possible, control of the body's center of gravity throughout the drill.
3. Keep an erect posture with a stable trunk and avoid excessive anterior pelvic tilt and rounded shoulders.
4. Keep the head and eyes up, looking straight ahead.
5. Keep the body weight evenly distributed over the balls of the feet.
6. Maintain the same angle of hip, knee, and ankle flexion throughout the drill, including during changes in direction. Knee flexion should be >30° (Fig. 18.2).

Fig. 18.1 (**a**) Valgus knee position on a sidecut, (**b**) loss of hip and knee flexion angles during deceleration just prior to a sidecut, (**c**) knee hyperextension and foot far in front of the center of body mass upon planting for a side-cut (Reprinted from Barber-Westin and Noyes [9])

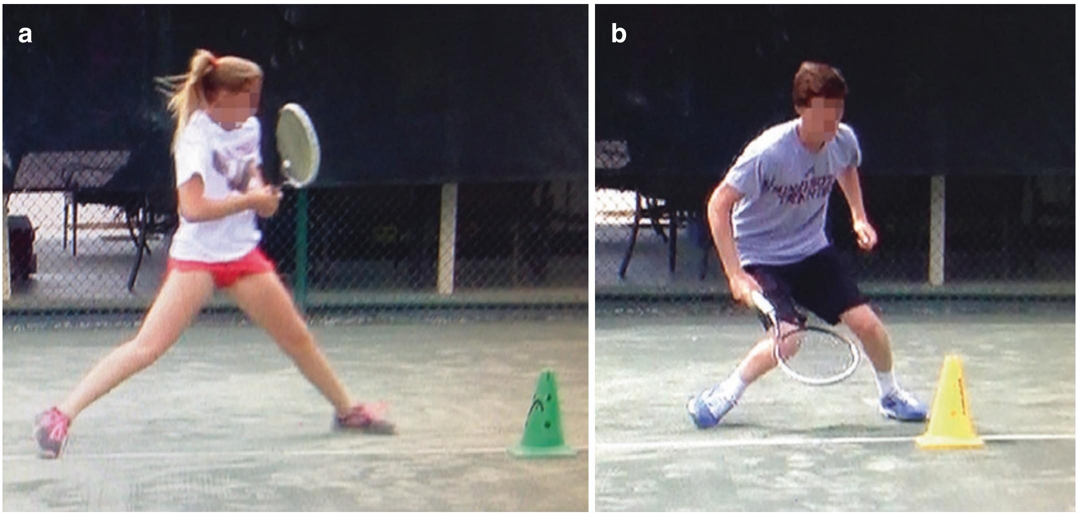


Fig. 18.2 Demonstration of a deceleration and lateral cut maneuver during the baseline forehand test (see Sect. 18.10.2) before the beginning of a Sportsmetrics Tennis training program. (**a**) A 16-year old female player demonstrates poor body positioning and control while attempting to decelerate and stop, with the knee fully extended and positioned far away from the center of body mass. (**b**) A 15-year-old male player shows a better technique for this maneuver; however, improvement was suggested for foot placement as the cut was made

7. Avoid a valgus lower limb position.
8. Keep the knees over the ankles and do not allow them to extend over the toes.
9. During deceleration, use three short steps to reduce speed instead of one step.
10. During a sidestep cut, bring the foot to the midline to plant and keep the torso upright, with no rotation, pointed in the general direction the athlete wishes to travel.
11. Videotape the athlete while they perform drills and exercises to show techniques that require correction.
12. The instructor should demonstrate the correct technique as often as required, asking the athlete to imitate what they see.

18.3 Agility and Reaction Drills

18.3.1 Shadow Swing Baseline, Forehand and Backhand

The athlete begins in the middle of the baseline, with the arms crossed so that the left hand is holding the right shoulder and the right hand is holding the left shoulder. The athlete runs to the singles sideline of their forehand and swings the torso and shoulders in a complete forehand motion (Fig. 18.3) that goes from the backswing to the follow-through. The athlete then runs back to the starting position. When going toward the deuce side, the left shoulder faces the court, then the chest becomes parallel to the baseline. The swing is finished with the right shoulder facing forward to accelerate the crossover recovery step. The athlete should be reminded to keep their head up to focus on the ball and help with balance. Shoulder turns are exaggerated.

18.3.2 Alternating Short/Deep Balls, Forehand and Backhand

The instructor feeds the athlete alternating short and deep shots by tossing the ball from the sideline (Fig. 18.4). With the athlete on the baseline, by the sideline of the forehand side, the instructor feeds a short ball (approximately by the service line) to the athlete's forehand. Then, as soon as the ball is hit, the instructor immediately feeds a deep ball back toward the baseline.

Fig. 18.3 Shadow swing baseline, forehand and backhand. (**a**) Starting position, (**b**) shoulder turn simulating forehand, and (**c**) completion of shoulder turn (Reprinted from Barber-Westin and Noyes [9])

The athlete must quickly change direction and move backward to be able to hit the shot correctly. The athlete is encouraged to hit a down the line approach shot on the short balls and either a crosscourt shot or a recovery lob on the deep balls. The athlete is also reminded to stay low and sideways for short balls and hit with an open stance.

18.3.3 Resistance Belt Forehand and Backhand

A resistance belt is applied to the athlete's waist which is held by another athlete or instructor. The athlete begins in the center of the baseline. The instructor feeds balls to the far sideline of the forehand, which the athlete hits and then recovers back to the starting position. A total of 10 consecutive balls are fed to the forehand. After a 30-s rest, the same drill is repeated to the backhand.

18.3.4 Rapid Drop Feed Forehand and Backhand

The athlete begins on the sideline of their forehand and the instructor stands a few feet in front and to the side of the athlete (in the doubles alley). The instructor drops eight consecutive balls to the forehand, which the athlete hits immediately after the ball strikes the ground. The instructor feeds the balls as rapidly as the athlete is able to hit. After a 10-s rest period, the drill is repeated on the backhand side. The athlete is instructed to keep the head down, keep the upper body as

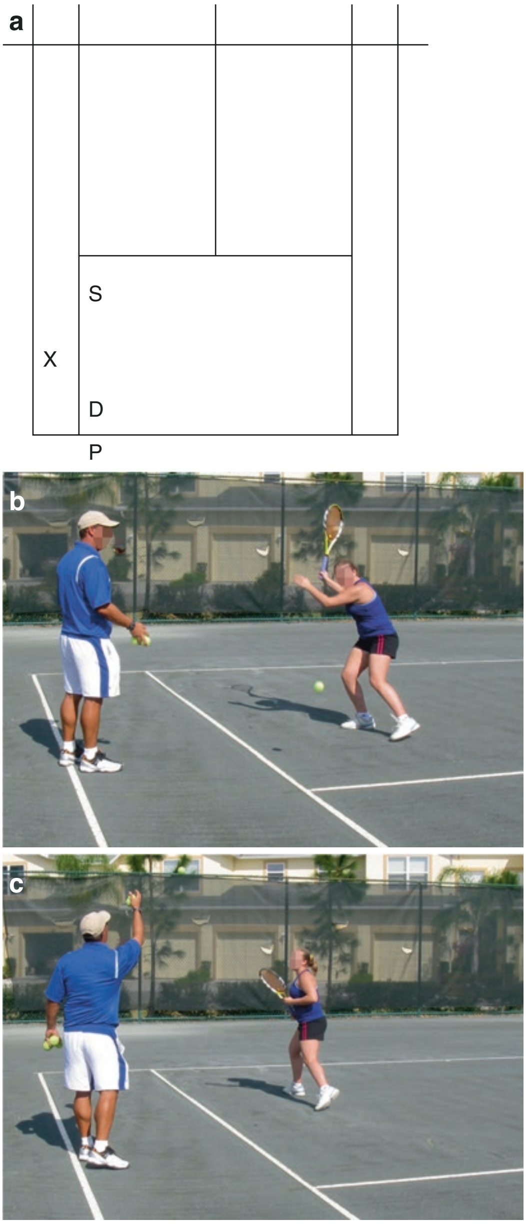


Fig. 18.4 Alternating short/deep balls forehand and backhand drill. *X* instructor; *P* player; *D* deep ball feed; *S* short ball feed. (**a**) Diagram showing positions, (**b**) short forehand shot, and (**c**) turn to prepare for deep forehand (Reprinted from Barber-Westin and Noyes [9])

stable as possible, make small adjustments with the feet, and stay low.

18.3.5 Forehand and Backhand Reaction, Facing Net

The athlete begins in the middle of the baseline facing the net, and the instructor is positioned on the same side of the court, approximately 7 ft. (2.1 m) in front of the athlete. The instructor holds three to four balls in each hand, with both hands held behind the back. On command, the instructor tosses a ball in a random fashion anywhere in the singles court between the baseline and service line. The athlete runs and hits the shot and recovers to the middle of the baseline. Eight ball tosses are completed, the athlete rests for 10 s, and then another set of eight shots are performed.

18.3.6 Forehand and Backhand Reaction, Facing Fence

The athlete begins in the middle of the baseline facing the fence, and the instructor is positioned on the same side of the court, approximately 7 ft. (2.1 m) in front of the athlete. The instructor holds three to four balls in each hand, with both hands held behind the back. On command, the instructor tosses a ball in a random fashion anywhere in the singles court between the baseline and service line. The athlete turns to face the court, runs and hits the shot, and recovers to the middle of the baseline. After each recovery, the athlete turns back around to face the fence. Ten ball tosses are completed, the athlete rests for 20 s, and then another set of 10 shots are performed. The athlete should be reminded to focus on the ball only and lean toward the side which the ball is tossed. The first move should be the shoulder turn, followed by an outside foot turn, and then a step.

18.3.7 Rapid Return Serve Feeds Forehand and Backhand

This drill is similar to "Rapid Drop Feed Forehand and Backhand"; however, the ball is not allowed to drop. The athlete hits the ball in the air to simulate a return of serve using a smaller backswing. The instructor feeds eight balls to the forehand as rapidly as possible. After a 10-s rest period, the drill is repeated on the backhand side.

18.3.8 Ladder Up-Up, Back-Back, Sprint to Groundstroke, Sprint to Volley, Forehand and Backhand

A ladder is positioned behind the baseline. The athlete proceeds through the ladder using the up-up, back-back pattern shown in Fig. 18.5. Upon completion, the athlete sprints to the opposite sideline and hits a groundstroke feed by the instructor. Then, the athlete sprints ahead diagonally to hit a volley on the opposite side of the court. In the diagram shown in Fig. 18.6, a right-handed player would hit a forehand groundstroke and then a backhand volley. After hitting the volley, the athlete side-shuffles off to the nearest doubles sideline and then backpedals to the ladder. The same pattern is continued for 90 s and then repeated with the ladder moved to the opposite side of the court.

18.4 Acceleration, Speed, and Endurance Drills

18.4.1 Suicides, 1-Court

Beginning on one doubles sideline, the athlete runs forward and touches the singles sideline with their racket, backpedals and touches the doubles sideline, runs forward and touches the center of the baseline, backpedals and touches the doubles sideline, and so on until all lines have been touched (Fig. 18.7). On clay courts, the athlete should be encouraged to slide into the line. On hard courts, small adjustment steps are emphasized.

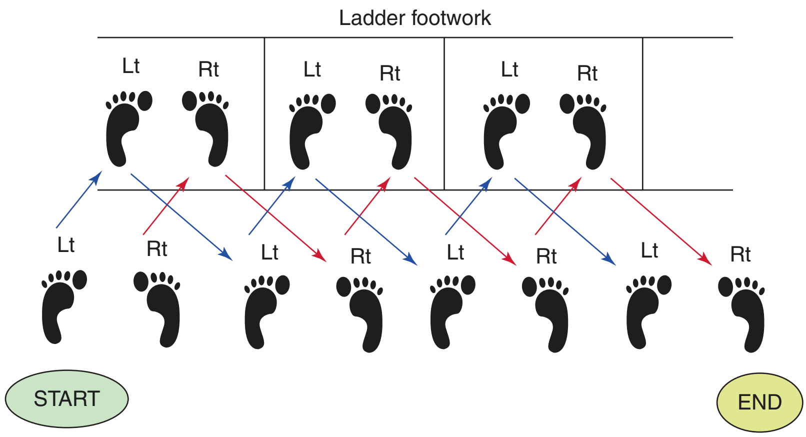


Fig. 18.5 Ladder footwork for ladder: up-up and back-back drill. Only a portion of the 4.6 m ladder is shown for illustrative purposes (Reprinted from Barber-Westin and Noyes [9])

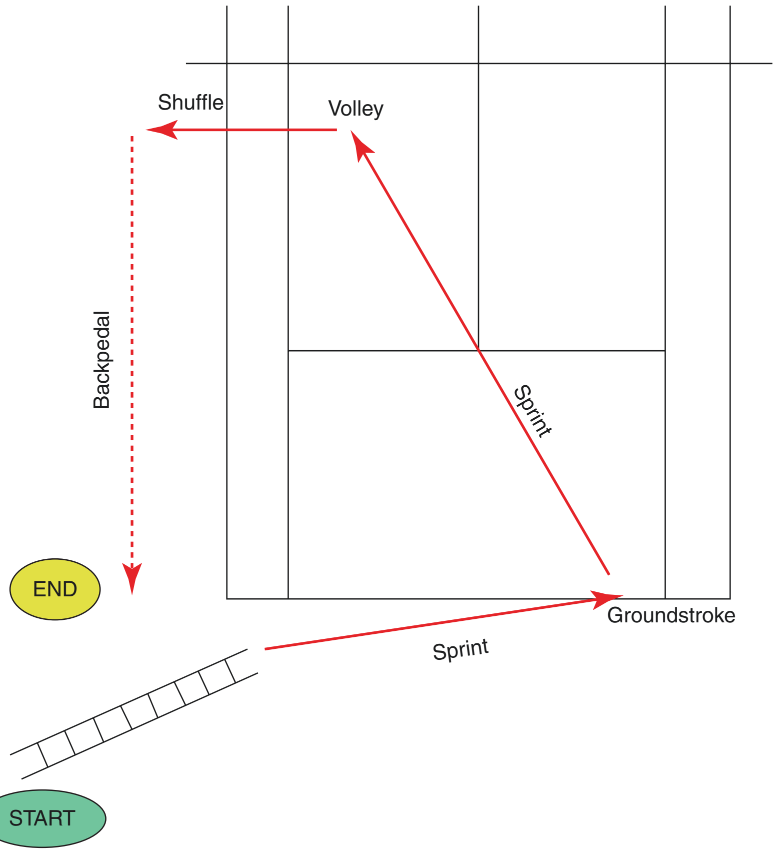


Fig. 18.6 Up-up, back-back, sprint to groundstroke, sprint to volley, forehand and backhand (Reprinted from Barber-Westin and Noyes [9])

18.4.2 Suicides, 2-Court

This drill is the same as described above, except the exercise is completed twice on one court, or once on a 2-court bank if available.

18.4.3 Net Zigzag

Five cones are placed in a zigzag pattern from the baseline to the net as shown in Fig. 18.8. The placement of the cones may be modified if the player needs to train on shorter or wider cuts. The athlete begins on the baseline, runs to the first cone and swings the racquet to simulate a volley directly over the cone. In the course depicted in Fig. 18.8, the first cone would indicate a forehand volley for a right-hand player. The athlete continues to the second cone and swings the racquet to simulate a backhand volley. This pattern is continued to the final cone at the net. Once the athlete has completed the final forehand volley at this cone, they turn and continue the pattern back to the baseline. In this drill, emphasis is placed on correct footwork both during running between cones and while volleying, keeping the knees bent, the head still, and body balanced throughout. To make this task more challenging, the instructor may stand behind the net and occasionally feed balls during the volleys.

18.4.4 Forehand and Backhand Wide Continuous Hitting

The athlete begins in the center of the baseline behind a cone. The instructor feeds balls to the

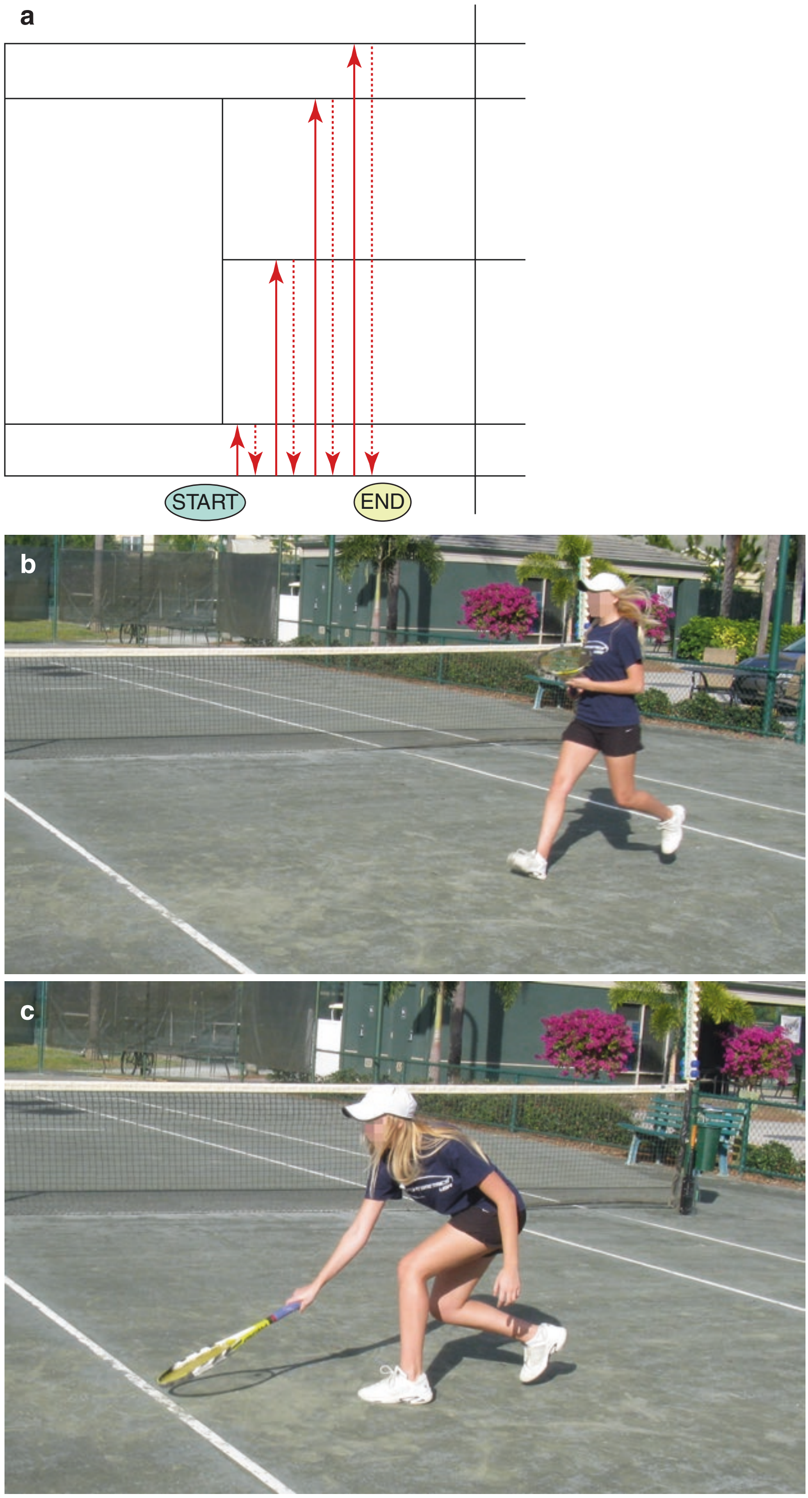


Fig. 18.7 The one-court suicide is run in a straight line; the figure depicts the eight segments individually for illustrative purposes only. (**a**) *Solid lines* indicate forward sprinting; *dotted lines* indicate backpedaling; (**b**, **c**) athlete performing the test (Reprinted from Barber-Westin and Noyes [61])

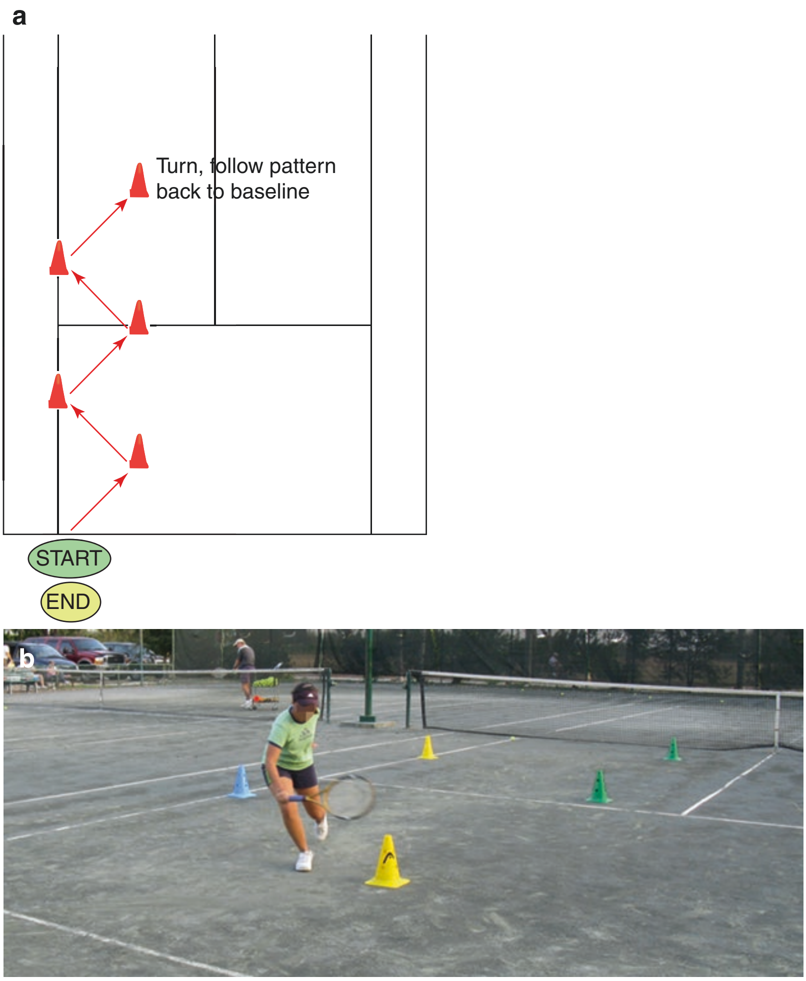


Fig. 18.8 Net zigzag drill: (**a**) diagram and (**b**) simulated volley over last cone (Reprinted from Barber-Westin and Noyes [9])

forehand and backhand, wide toward each sideline, for the durations shown in Table 18.1. After each shot, the athlete must return to the cone at the center of the baseline. The athlete is reminded to focus on recovery footwork and to breathe continuously.

18.4.5 Baseline Random Feed Forehand and Backhand

The athlete begins in the middle of the baseline. The instructor randomly feeds balls to the forehand and backhand, within 4–6 ft. (1.2–1.8 m) of the player, for 1 min without stopping. The athlete rests for 30 s, and then the instructor randomly feeds another round of groundstrokes for 2 min without stopping. The athlete is reminded to focus on recovery footwork and to breathe continuously.

18.4.6 Sprint-Quick Feet-Listen to Instructor

The athlete begins sprinting the length of the court. During the sprint, the instructor commands “stop” at any time, at which point the athlete stops in place, but keeps their feet moving quickly in the same spot until the instructor commands "go".

18.5 Ladders, Quick Feet, Additional Jump Drills

18.5.1 Ladder: Up-Up, Back-Back, Sprint to Cone, Backpedal

A 15-ft (4.6 m) ladder is placed parallel to and 6 ft. (1.8 m) behind the baseline. A cone is placed 4 ft. (1.2 m) from the net and in line with the end of the ladder. The athlete proceeds through the ladder using the up-up, back-back pattern (see Fig. 18.5) and then sprints forward to the cone, touches the cone with their racquet, and then runs backward in a controlled, balanced manner (Fig. 18.9).

18.5.2 Backward Broad Jump

The backward broad jump is done by beginning in an athletic stance with the knees deeply flexed and then jumping backward as far as possible, taking off with both feet. The athlete lands on both feet together, remains in a deep crouch position for 5 s, and then repeats the jump.

18.5.3 Pattern Jumps

A series of 10 jumps are performed in a 4-square pattern configuration with tasks of increasing difficulty (Fig. 18.10). Each square is approximately 2 × 2 ft. (0.6 × 0.6 m). Two pattern jumps are performed each week, beginning the second week of training as the final jump/plyometric component. The player begins in box #1 and follows the num-

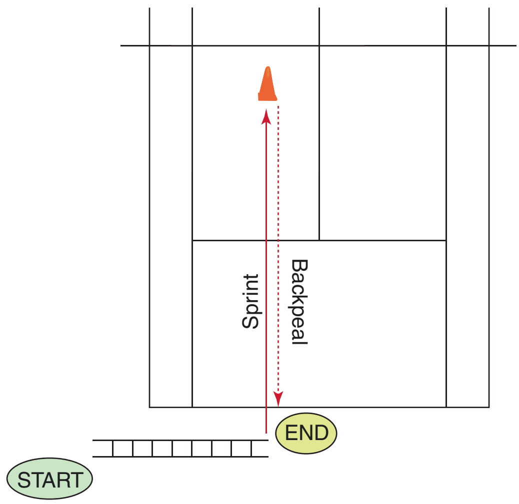


Fig. 18.9 Ladder: up-up, back-back, sprint to cone, backpedal (Reprinted from Barber-Westin and Noyes [9])

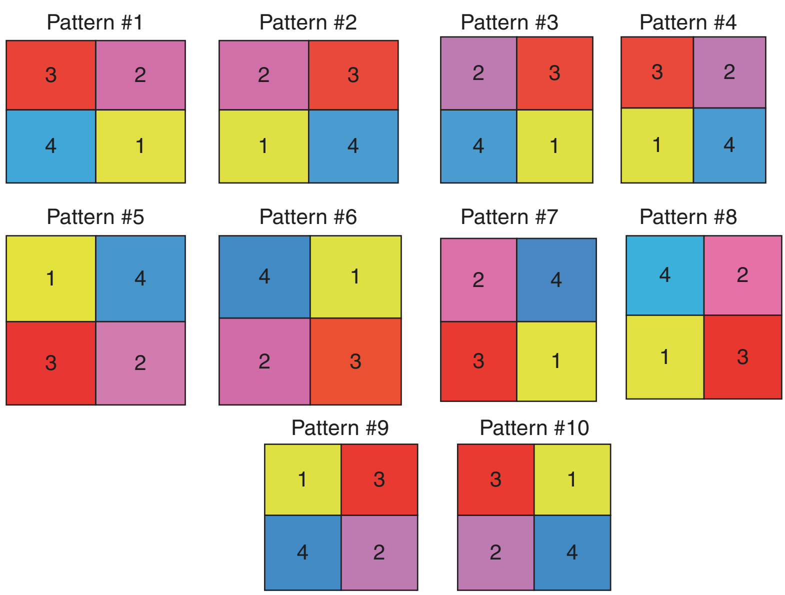


Fig. 18.10 Pattern jumps (Reprinted from Barber-Westin and Noyes [9])

bers in consecutive order, jumping into each box without landing on the lines. After reaching box #4, the player returns to box #1 and repeats the pattern. The player is encouraged to practice each pattern two to four times first to learn the task.

18.6 On-the-Court Strength Training

In addition to the strength training exercises described in Chap. 14, other options were designed for Sportsmetrics Tennis that may be accomplished at the tennis facility. The equipment required include a medicine ball (2 pounds [0.9 kg] minimum, heavier weighted balls for stronger players), hand-held weights (two weights each, 2–10 pounds [0.9–4.5 kg], in 1-pound [0.4 kg] increments), and large plastic balls or cushions for the wall-sitting exercises.

18.6.1 Medicine Ball Forehand, Backhand, Overhead, Between Legs

The medicine ball exercises focus on replicating the motions of the forehand, backhand, and overhead in order to strengthen the muscles used in those strokes. For the forehand and backhand exercises, two athletes should stand 6–8 ft. (1.8–2.4 m) apart. One athlete begins by holding the ball with both hands on their forehand side. The athlete turns and takes the ball back in a motion similar to the forehand backswing, then steps into a forehand swinging motion and passes the ball to the partner during the follow-through (Fig. 18.11). Both athletes should be constantly bouncing on their toes, keeping their feet moving throughout the exercise. The partner then performs the same motion, and the ball is tossed back and forth. The exercise is then done by mimicking a backhand motion.

Fig. 18.11 Medicine ball forehand, backhand showing (**a**) exaggerated shoulder turn and (**b**) ball toss to partner (Reprinted from Barber-Westin and Noyes [9])

For the overhead exercise, one athlete takes the ball and holds it with both hands over their head. Using both arms together, the athlete steps forward with the front leg used in their overhead motion (i.e., left leg for a right-handed player) and throws the ball forward a few feet and down to the ground with as much force as possible. The ball is caught after one bounce by the partner, who repeats the motion. In the final medicine ball exercise, one athlete turns so that their back faces their partner. The athlete spreads their legs and bends the knees and hips, placing the ball on the ground between their legs. Just as a center in American football "hikes" the ball to the quarterback, the athlete uses both hands to toss the ball to the partner.

18.6.2 ETCH-Swing Forehand, Backhand, Serve

This drill uses the commercially available ETCH-Swing training device. This device is similar to a racquet, except that in place of the head and strings are four blades which provide resistance when going through the motions of tennis strokes. The athlete simulates 15 forehands in a continuous manner, 15 backhands, and 15 first serves (Fig. 18.12). The instructor should make sure that the athlete is swinging the device in the same manner as their normal strokes, focusing on accelerating through the stroke as quickly as possible. After a 30-s rest, the athlete simulates 15 forehands, 15 backhands, and 15 s serves.

18.6.3 Backward Lunge

The athlete begins by stepping backward with one leg as far as possible. Keeping the back straight, the back leg is lowered toward the ground, stopping just before the knee touches the ground or as low as possible while maintaining balance and control. The front knee should stay directly over the ankle. The athlete lifts up and brings the front leg alongside the back leg, pauses, and then repeats this pattern for the duration shown in Table 18.1. During training session #4, the athlete should add dumbbell weights (equal weight in both hands) during this exercise. The amount of weight should make the task more challenging, but not cause the athlete to lose balance and control of the correct posture (Fig. 18.13).

18.6.4 Twisting Lunge with Medicine Ball

The athlete begins at the baseline in an athletic position, holding a medicine ball with both hands in front of the body. The athlete steps the right leg forward and performs a lunge exercise, maintaining a straight back and bending the knees so that the back knee is almost touching the ground. Holding this position, the athlete rotates the upper body and arms to the right as far as possible and then to the left as far as possible. The athlete then lifts the body up to standing by initiating the lift up with the back leg. The back leg is brought alongside the front leg and paused, and then the exercise is repeated with the opposite (left) leg.

18.6.5 Toe Walking

The athlete walks continuously on their toes for the designated distance. The entire court is used by walking from one baseline to the other baseline, just off one far side of the court in order to go in a straight line and avoid the net.

18.6.6 Wall Push-Ups

For athletes with limited upper body strength, wall push-ups offer an initial challenge which is safe and effective in working the major muscle groups of the shoulder. The athlete stands approximately 3 ft. (0.9 m) away from a wall and, keeping the back straight, leans toward the wall and places both hands on the wall approximately in line with the shoulders, keeping them shoulder-width apart. The athlete slowly leans the body forward so that it almost touches the

Fig. 18.12 ETCH-swing drills for (**a**, **b**) forehand, (**c**, **d**) backhand, and (**e**, **f**) serve (Reprinted from Barber-Westin and Noyes [9])

Fig. 18.12 (continued)

Fig. 18.13 Backward lunge with hand-held weights (Reprinted from Barber-Westin and Noyes [9])

wall. This position is held for 1–2 s and then the athlete slowly pushes back off of the wall to the starting position. Athletes with appropriate body strength should perform regular ground push-ups.

18.6.7 Wall Sits

The athlete sits against a wall with the knees at approximately 90°, the back straight, and the legs and knees kept shoulder-width apart. The hands are relaxed at the side. One variation of the wall-sit exercise requires that the athlete squeeze a ball or cushion between their thighs as strongly as possible for the duration of the task. Another option entails the athlete holding dumbbell weights in their hands to increase body weight. If the athlete experiences kneecap pain, the amount of knee flexion should be decreased by having the athlete should sit up "straighter" against the wall.

18.6.8 TheraBand Crab Walking (Lateral Lunges)

A TheraBand resistance exercise loop is placed just above (and outside) the athlete's ankles. Crouching as low as possible, the athlete slowly performs lateral lunges by stepping out sideways as far as possible with the outside leg and then bringing the opposite leg under the body. The knees and hips should remain at the same angle throughout the exercise. The outside leg should be stretched so the resistance band becomes as tight as possible. This exercise is then progressed beginning with training session #7. Two athletes stand a few feet apart and, with the TheraBand in place, side shuffle at a comfortable jogging pace, making sure their feet do not drag on the ground. A medicine ball is passed back and forth (chest passes). As the athletes' confidence grows, the pace can be increased as fast as possible, maintaining the deep crouch position.

18.6.9 Ball-Wall Exercises

Several exercises may be used with tennis balls or medicine balls against a wall for upper body and core strengthening. In the drill entitled *tennis ball, small circles*, the athlete faces a wall and stands 1–2 ft. away. While holding a tennis ball, the athlete raises one arm to a 90° angle (Fig. 18.14a). The tennis ball is moved in small, tight circles of no more than a few inches in any direction. The 90° arm position should be maintained throughout the exercise. The exercise is also done with the athlete turned to the side as shown in Fig. 18.14b.

For the medicine ball overhead dribble exercise, the athlete faces a wall and stands 1-2 ft. away. The athlete raises both arms and rapidly dribbles the medicine ball against the wall, catching and dribbling with both hands (Fig. 18.14c).

The medicine ball sideways core toss against the wall exercise is shown in Fig. 18.14d, e. The athlete may assume either an open-stance or closed-stance position toward a wall based on their size and strength. The exercise is performed in a similar manner as the medicine ball forehand and backhand drill, only the ball is tossed against the wall and caught without bouncing. The ball should be thrown as hard as possible, with the forehand and backhand motions exaggerated. The athlete's stance should be maintained throughout the exercise.

18.7 Lower Extremity Power and Dynamic Balance Tests

18.7.1 Single-Leg Hop

Single-leg functional hop tests are one of the most commonly used measures of lower extremity power and dynamic balance [62–66]. These tests determine if abnormal lower limb symmetry exists and subjectively assess an athlete's ability to hop and hold the landing on one leg [15]. They are highly reliable and require only a tape measure which is secured to the ground. Our research demonstrated that a limb symmetry index of ≥85% is present in the majority (93%) of athletes [67].

If a video camera is available, it is recommended that the single-leg hop tests be recorded. On a subjective basis, one may observe if the player has the ability to "stick and hold" the landing with the knee and hips flexed, demonstrating adequate control of the core and upper extremity, as well as the lower extremity (Fig. 18.15a). Some players may be able to hold the landing, but their knee may wobble back and forth, along with poor upper body control and posture (Fig. 18.15b). In some instances, players will not be able to hold the landing at all and may even fall toward the ground (Fig. 18.15c). These players should be encouraged to practice single-leg balance exercises daily, along with single-leg strength training exercises several times a week to improve this problem.

For the single-leg hop test, a tape measure is secured to the ground for a distance of approximately 3 m. The athlete stands on the designated leg to be tested with their toe just behind the starting end of the tape. They are instructed to hop as far as possible forward and land on the same leg, holding that position for at least 2 s (s) [15,

Fig. 18.14 Medicine ball-wall exercises. (**a**, **b**) Tennis ball small circles. (**c**) Overhead dribble. (**d**, **e**) Sideways core toss against wall (Reprinted from Barber-Westin and Noyes [9])

Fig. 18.14 (continued)

67]. The athlete is allowed to use their arms for balance as required. After a few trials, the athlete completes two single-leg hops on each limb. The distance hopped is recorded and the furthest distance achieved is used to calculate limb symmetry by dividing the distance hopped of the right leg by the distance hopped of the left leg, and multiplying the result by 100. This test has excellent reliability, with ICC > 0.85 [69, 70]. Significant correlations have been reported between limb symmetry scores for this test and knee extensor peak torque tested isokinetically [67, 71–73].

18.7.2 Single-Leg Triple Crossover Hop

A tape measure is secured to the ground for a distance of approximately 6 m. The athlete stands on the leg to be tested with their toe just behind the starting line. Three consecutive hops are done on that leg, crossing over the measuring tape on each hop. The athlete must be in control and hold the landing of the third hop for 3 s for the test to be valid [15]. The athlete may use their arms for balance as required. After a few practice trials, two single-leg triple crossover hops are done on each limb. The total distance hopped is measured, and the right-left leg limb symmetry index calculated as described above. This test has excellent reliability, with ICC > 0.85 [69, 74]. Significant correlations have been reported between limb symmetry scores for this test and knee extensor peak torque tested isokinetically [72].

18.7.3 1-Repetition Maximum Leg Press

A 1-repetition maximum (1RM) leg press may be performed if weight room equipment, an experienced test administrator, and a sufficient amount of time to safely conduct the test are available [75, 76]. Adequate reliability of the 1RM test has been documented in several investigations [77–80]. Seo et al. [80] recommended the following reliable protocol:

(1) Warm up for 5 min on a stationary bicycle, rest for 1 min.
(2) Complete 8–10 repetitions of a light load, ~50% of predicted 1RM, rest for 1 min.
(3) Complete 1 load of ~80% of predicted 1RM through full range of motion, rest for 1 min. After each successful lift, increase the weight until a failed attempt occurs. Allow 1 min of rest between each attempt.
(4) The 1RM will usually be attained within 5 attempts.

18.7.4 Countermovement Vertical Jump

The countermovement vertical jump test is one of the most commonly used measures to assess anaerobic power. Many methods have

Fig. 18.15 Single-leg hop for distance video screening allows a qualitative assessment of an athlete's ability to control the upper and lower extremity upon landing, which may be rated as either good (**a**), fair to poor (**b**), or complete failure, fall to ground (**c**) (Reprinted from Barber-Westin and Noyes [68])

been described to measure vertical jump height and some authors recommend using contact mats to obtain measurements such as contact and flying times [3, 17]. A cost-effective measure of the vertical jump may be done with the Vertec Jump Training System (Sports Imports, Columbus, OH) [81]. First, the athlete's standing reach is measured with the athlete standing with both heels touching the ground. Then, a countermovement vertical jump with arm swing is performed three times and the highest jump obtained recorded (Fig. 18.16).

Fig. 18.16 Vertical jump test using Vertec (Reprinted from Barber-Westin and Noyes [61])

Reliability for the assessment of vertical jump height using this method is excellent, with ICCs >0.90 [82, 83].

18.8 Upper Body Strength and Power Tests

18.8.1 Sitting Chest Pass

The sitting chest pass is a convenient way to assess upper body strength [19, 84–86]. The player sits on the floor with their head, back, and buttocks against a wall. Their legs rest straight horizontally on the floor in front of their body (Fig. 18.17). The player is asked to push a basketball in the horizontal direction as far as possible using a 2-handed chest pass. Three trials are completed, with the farthest toss recorded. Excellent reliability (ICC 0.98) and positive correlations have been reported between this test and isokinetic shoulder and elbow strength ($R = 0.59$–0.80) [19].

18.8.2 Standing Medicine Ball Toss: Chest Pass, Forehand Backhand, Overhead

The medicine ball toss is another commonly used test to measure upper body strength and power [22, 87]. The athlete stands one step behind a

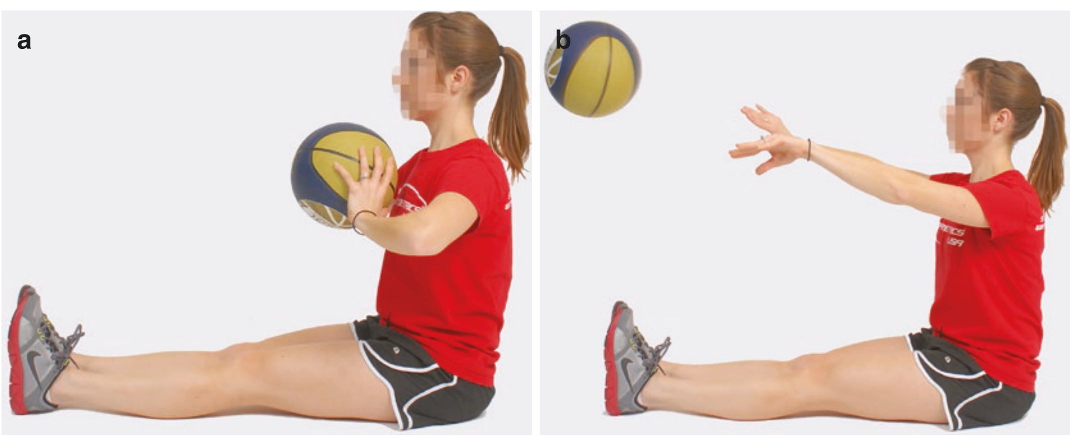


Fig. 18.17 (**a**, **b**) Sitting chest pass Reprinted from Barber-Westin and Noyes [61])

line with a medicine ball. They take one step and toss the ball, making sure not to cross over the line. There are three variations for the toss, the most frequent being a pass at chest level. In tennis players, the throw may simulate the forehand, backhand, or overhead [22] (Fig. 18.18a–d). Three trials are completed, with the farthest toss recorded. Significant correlations were reported between this test and isometric maximum trunk rotation torque (R = 0.61–0.69) and

Fig. 18.18 Medicine ball toss (**a**, **b**) Backhand. (**c**, **d**) Overhead. Reprinted from Barber-Westin and Noyes [61])

1-repetition maximum bench press for male athletes (R = 0.60–0.65) [88]. In elite male and female tennis players, significant correlations were reported between isokinetic trunk rotation peak torque and the distance tossed in both the forehand (R = 0.81–0.84) and backhand sides (R = 0.82–0.85) [20].

18.8.3 1-Repetition Maximum Bench Press

A 1-repetition maximum (1RM) bench press may be performed if weight room equipment, an experienced test administrator, and a sufficient amount of time to safely conduct the test are available [75, 76].

(1) Warm up for 5 min on a stationary bicycle or rowing machine, rest for 1 min.
(2) Complete 8–10 repetitions of a light load, ~50% of predicted 1RM, rest for 1 min.
(3) Complete 1 load of ~80% of predicted 1RM through full range of motion, rest for 1 min. After each successful lift, increase the weight until a failed attempt occurs. Allow 1 min of rest between each attempt.
(4) The 1RM will usually be attained within 5 attempts.

18.9 Abdominal Strength and Endurance Tests

18.9.1 Sit-Up Test

Sit-up tests may be used to assess muscular strength and endurance. With the athlete lying supine with the knees bent and foot flat on the floor (held in place by a partner) and arms folded across the chest, sit-ups are performed by raising up so that the elbows touch the knees and then lower back so the shoulders touch the floor. The test may either include the number of repetitions completed in 60 s or may be done until exhaustion (execution until failure). Investigations have demonstrated adequate reliability of sit-up tests in normal subjects of 0.84 (reliability coefficient) [89] and chronic pain populations of 0.77 (ICC, test-retest) and 1.00 (ICC, inter-rater) [90].

18.9.2 Abdominal Endurance Test

Abdominal endurance may be measured by positioning the athlete on a mat or cushion on their back with their arms by their side while sitting on their hands. Upon command, both legs are lifted together approximately 15 cm off the ground and the athlete is instructed to maintain this position for as long as possible. The amount of time that the athlete is able to stay in this position (keeping both legs off of the ground) is recorded with a digital stopwatch.

18.10 Speed and Agility Tests

18.10.1 1-Court Suicide

The athlete begins on the doubles sideline and runs at maximal speed to four different lines: the near singles sideline, the center of the baseline, the far singles sideline, and the far doubles sideline (see Fig. 18.7) [21]. When they arrive at each line, the line is touched with the racquet and the athlete backpedals to the original doubles sideline. The time to complete this test is recorded with a digital stopwatch in one-hundredths of a second. A 2-court suicide run may also be done either by completing this course twice or on a bank of 2 side-by-side courts.

18.10.2 Baseline Forehand and Backhand Tests

The baseline forehand and backhand tests are useful speed and agility tests for tennis players [21]. A cone is placed in the center of the baseline and on the singles sideline of the player's forehand side, 0.9 m inside the court (Fig. 18.19). The athlete begins on the center of the baseline and upon command, runs to the

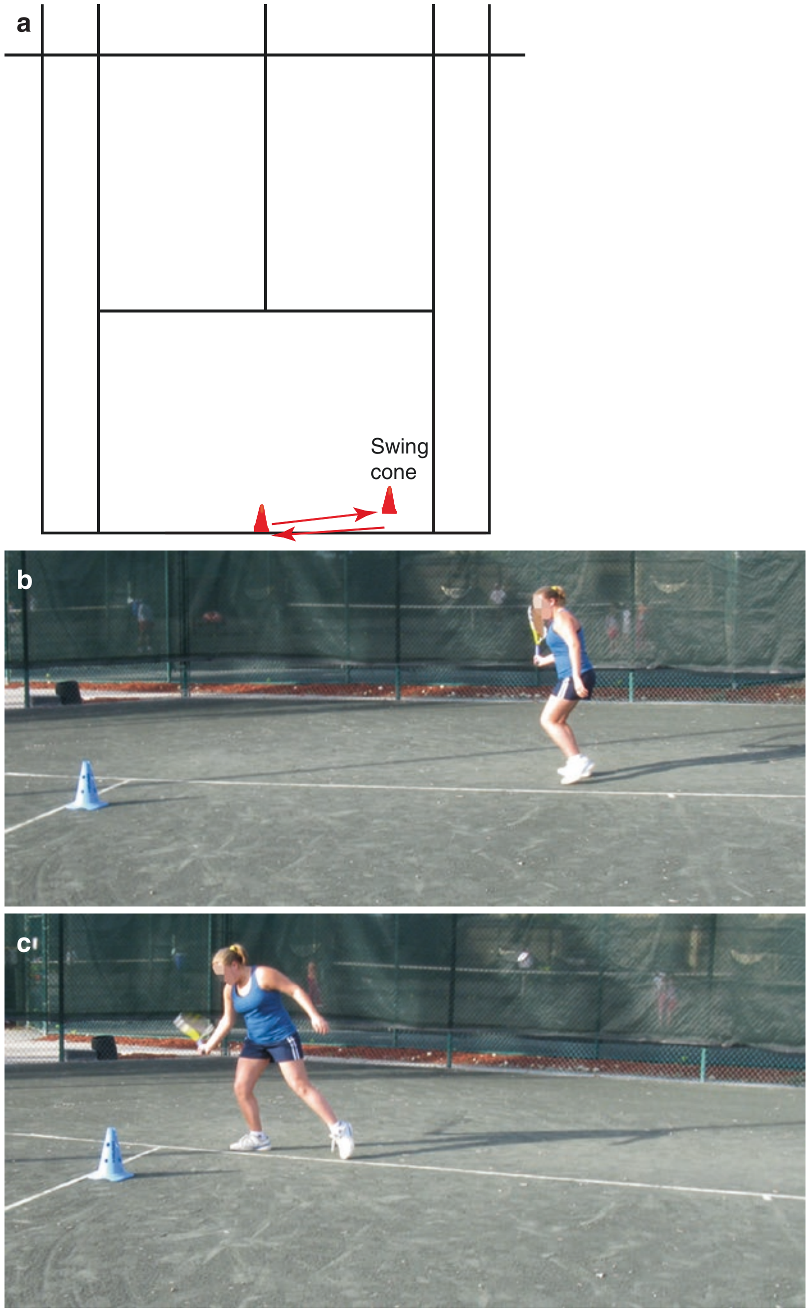


Fig. 18.19 (**a**) Baseline speed and agility forehand and backhand test; (**b**–**c**) an athlete performing the test on the forehand side (Reprinted from Barber-Westin and Noyes [61])

cone on the sideline, completes a forehand swing with the racquet, runs back to the starting position, and continues back and forth for a period of 30 s, which is timed with a digital stopwatch. One repetition equals one full run from the center of the baseline to the swing cone and back to the center, or a distance of 5 m. The number of repetitions completed in the 30-s time period is recorded and converted to the total distance covered. If a player reaches the swing cone at the end of the 30 s, ½ of a repetition is added to the total count. The test is then done with the swing cone placed on the singles sideline of the player's backhand.

18.10.3 Service Box Test

The service box test is another appropriate speed and agility test for tennis players [21]. The athlete begins in the middle of the service box in an athletic position. Upon command, they run and touch the center service box line and then touch the singles sideline with their racquet, going back and forth as many times as possible within 30 s (Fig. 18.20). Each time the player touches a line counts as 1 repetition. The distance between the two lines is 1.1 m. The player performs this test twice, with a 5-min rest between tests. The mean number of repetitions is calculated and converted to the total distance covered. This test has acceptable reliability, with an ICC of 0.85 [21].

18.10.4 10-M and 20-M Sprint

The 20-m sprint test, with a split at 10-m, may be used as a general measure of linear accelera-

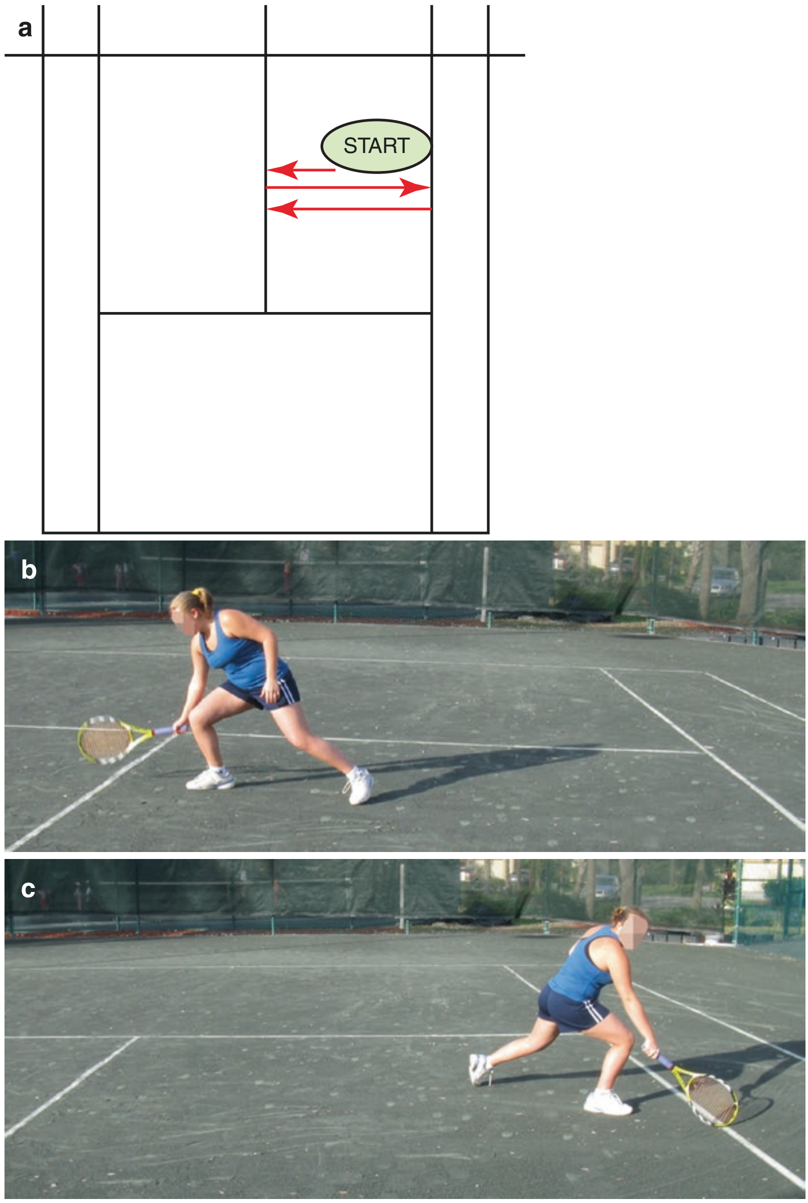


Fig. 18.20 (**a**–**c**) Service box speed and agility test (Reprinted from Barber-Westin and Noyes [61])

tion and speed. This test is usually included in the testing of national federations [17, 91] and although shorter distances (5-m and 10-m) are more specific to tennis, the speed recorded over 20 m is informative.

18.11 Aerobic Fitness Tests

18.11.1 Multistage Fitness Test

Aerobic fitness is a critical component for athletic performance and injury prevention [92]. Maximal oxygen uptake (VO_2max) is most accurately measured using laboratory tests; however, they are expensive, time-consuming, and require trained personnel. One of the most common field assessments is the 20-m multistage fitness test (MSFT) [24]. This test has been used by different national tennis federations, such as the USTA, the French Tennis Federation, and Tennis Australia [28, 91, 93], and the results (VO_2max) have been shown to correlate with player ranking in elite players [28].

The equipment required are the MSFT commercially available audio compact disc (CD) and a CD player. Two cones are used to mark the course (Fig. 18.21). The athlete begins with their toes behind the designated starting cone. The second cone is located 20 m away. The athlete is instructed that, on the "go" command, they are to begin running back and forth between the two cones in time to recorded beeps on the CD. The athlete performs shuttle runs back and forth along the 20-m course, keeping in time with the series of signals (beeps) on the CD by touching the appropriate end cone in time with each audio signal. The frequency of the audible signals (and hence, running speed) is progressively increased until the athlete reaches volitional exhaustion and can no longer maintain pace with the audio signals, indicated when three beeps are missed in a row. The athletes' level and number of shuttles reached before they were unable to keep up with the audio recording are recorded (see Chap. 20, Table 20.7). The athletes' VO_2max is estimated using the equation described by Ramsbottom et al. [94]:

$$VO_2\,\text{max} = (5.857 \times \text{speed on the last stage}) - 19.458$$

Test-retest reliability of the MSFT has been reported to be excellent, with ICCs ≥0.90 [24, 95–97]. Eriksson et al. [25] reported ICCs >0.90 for reliability determined within the same day and between days in tennis players. The validity of this test in regard to estimating cardiorespiratory fitness has also been calculated to be acceptable [98].

18.11.2 Intermittent Recovery: Yo-Yo Test Level 1 and Level 2

The Yo-Yo Intermittent Recovery Test was developed to measure an athlete's ability to repeatedly perform intense exercise [99]. There are 2 test levels: level 1 (Yo-Yo IR1) and level 2 (Yo-Yo IR2). Level 1 is designated for lesser trained individuals and level 2 is appropriate for elite and highly trained athletes. Several studies have reported high reliability, reproducibility and sensitivity of the Yo-Yo tests to detect change resulting from training programs.

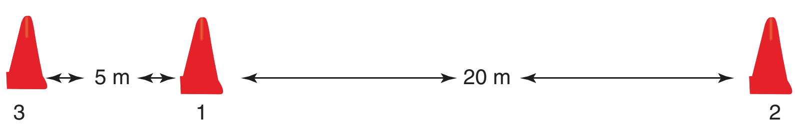


Fig. 18.21 Course used for the 20-m multistage fitness test (cones #1 and #2 only) and the 20-m Yo-Yo intermittent test (cones #1, #2, and #3) (From Barber-Westin and Noyes [61])

The Yo-Yo recovery test is conducted in a manner similar to the MSFT; however, periods of 10-s of rest are incorporated after each 2 × 20-m shuttle run until the athlete is exhausted. The equipment required are commercially available software (from which a CD may be made), or a commercially available audio CD, and a CD player. Three cones are used to mark the course as shown in Fig. 18.21. The athlete begins with their toes behind the designated starting cone (cone #1 in Fig. 18.21). The second cone is located 20 m away. The athlete is instructed that, on the "go" command (which is an audible beep on the CD), they are to run to the second cone and then return to the starting position when signaled by the recorded beep. They may jog or walk around the third cone and then turn back to the starting cone during a 10-s rest period. The athlete continues to perform this pattern, keeping in time with the series of signals (beeps) on the CD. The frequency of the audible signals (and hence, running speed) is progressively increased until the athlete reaches volitional exhaustion and can no longer maintain pace with the audio signals. The athletes' level and number of shuttles reached before they were unable to keep up with the audio recording are recorded.

The level 1 test usually takes 10–20 min to complete and level 2, 5–15 min [99]. The athlete's score is the total distance covered before they are unable to keep up with the recording (see Chap. 20, Tables 20.11 and 20.12). Although calculations exist for estimating VO_2max using the Yo-Yo test, investigators do not recommend this analysis due to high subject variability previously reported [99]. Instead, it is recommended that the total distance recorded be used to evaluate an athlete's ability to repeatedly perform intermittent exercise. Reliability for these tests is high, with ICCs >0.90 [100, 101].

18.12 Results of Program

Sportsmetrics Tennis was conducted and validated in a group of male and female junior players [21, 36] who participated in high school and USTA Level 6–7 tournament play [37]. Two prospective studies were conducted that included 42 players (31 females, 11 males; mean age, 14 ± 2 years) who completed at least 14 of the 18 training sessions [21, 36]. All training sessions were supervised by a tennis professional certified by the U.S. Professional Tennis Association and a certified Sportsmetrics instructor and were conducted on clay courts (Har-Tru) for 1.5 h per session. After training, significant improvements (and moderate to large effect sizes) were found for all field tests (Table 18.6). No subject sustained an injury that resulted in loss of time training or that required formal medical attention. A subgroup of 15 athletes participated in

Table 18.6 Summary of effect of Sportsmetrics tennis program on athletic performance indices[a]

	Measurement	Pre-train Mean ± SD	Post-train Mean ± SD	*P* value	Effect size
Strength and power	Single-leg hop, right leg (cm)	128.2 ± 28.5	141.8 ± 22.8	0.0004	0.53
	Single-leg hop, left leg (cm)	129.5 ± 27.1	138.3 ± 26.0	0.0007	0.33
	Single-hop triple crossover hop, right leg (cm)	340.7 ± 71.9	373.6 ± 70.1	0.006	0.46
	Single-hop triple crossover hop, left leg (cm)	340.5 ± 77.6	374.3 ± 78.4	0.004	0.43
	Abdominal endurance (s)	87 ± 56	162 ± 98	<0.0001	0.94
Speed and agility	1-court suicide (s)	18.55 ± 1.68	16.04 ± 1.23	<0.0001	1.70
	Baseline backhand (no. reps)	8.5 ± 0.9	9.2 ± 0.7	<0.0001	0.88
	Baseline backhand, total distance (m)	42.8 ± 4.6	46.3 ± 3.6	<0.0001	0.85
	Service line (no. reps)	22.4 ± 2.9	24.5 ± 2.2	<0.0001	0.82
	Service line, total distance (m)	89.4 ± 11.8	97.8 ± 8.9	<0.0001	0.80
	Baseline forehand (no. reps)	8.6 ± 1.0	9.3 ± 0.8	<0.0001	0.77
	Baseline forehand, total distance (m)	43.2 ± 5.1	46.8 ± 4.2	<0.0001	0.77

[a]From Barber-Westin et al. [9]

Table 18.7 Improvements in speed, agility, and abdominal endurance tests in players who completed more than one training program[a]

	First training session			Second training session			Third training session		
Test	Mean ± SD	*P*	ES	Mean ± SD	*P*	ES	Mean ± SD	*P*	ES
1-court suicide (s)	2.56 ± 1.17 (0.26–4.54)	<0.0001	1.63	1.11 ± 1.07 (−1.00–3.10)	0.0003	1.36	0.96 ± 0.032 (0.51–1.37)	0.004	0.73
Baseline forehand (m)	4.6 ± 3.9 (0–15.1)	0.0004	1.01	2.6 ± 3.5 (−2.5–7.5)	0.01	0.73	3.8 ± 2.9 (0–7.5)	0.02	1.33
Baseline backhand (m)	4.8 ± 3.2 (−1.2–10.0)	<0.001	1.07	1.6 ± 4.2 (−7.5–8.9)	NS	0.46	2.7 ± 2.3 (0–5.0)	0.02	0.89
Service line (m)	12.3 ± 11.3 (−4.1–45.1)	<0.001	1.30	3.2 ± 9.9 (−16.4–26.7)	NS	0.32	11.6 ± 10.8 (3.9–32.9)	0.03	0.73
Abdominal endurance (s)	84 ± 98 (−6−396)	0.005	1.02	70 ± 89 (−10–301)	0.01	1.20	111 ± 86 (41–262)	0.02	0.95

Data shown are mean ± SD (range) and effect size (ES) for the difference between tests conducted before and upon completion of each training program. Positive values indicate improvements, except for the 1 court suicide where the negative mean difference represents improved speed. *NS* not significant
[a]From Barber-Westin et al. [9]

more than one training program. The number of training programs completed were: 2 programs, 15 players; 3 programs, 7 players; 4 programs, 4 players; 5 programs, 2 players, and 6 programs, 1 player. Statistically significant improvements (and moderate to large effects sizes) were found for speed and agility and abdominal endurance tests after the first, second, and third training programs (Table 18.7). This program appears to be safe and effective in improving neuromuscular and athletic performance indicators in young tennis players and may be recommended as end-stage rehabilitation after a knee injury or surgery prior to return to competitive play.

References

1. Pluim BM, Miller S, Dines D, Renstrom PA, Windler G, Norris B, Stroia KA, Donaldson A, Martin K. Sport science and medicine in tennis. Br J Sports Med. 2007;41(11):703–4.
2. Kibler WB, Safran MR. Musculoskeletal injuries in the young tennis player. Clin Sports Med. 2000;19(4):781–92.
3. Fernandez-Fernandez J, Ulbricht A, Ferrauti A. Fitness testing of tennis players: how valuable is it? Br J Sports Med. 2014;48(Suppl 1):i22–31. https://doi.org/10.1136/bjsports-2013-093152.
4. Kibler WB, Safran M. Tennis injuries. Med Sport Sci. 2005;48:120–37.
5. Chevinsky JD, Shah NV, Tretiakov M, Aylyarov A, Penny GS, Dekis JC, Chorney JN, Ahmed N, Sodhi N, Wilhelm AB, Urban WP, Paulino CB, Newman JM. Demographics of tennis-related injuries that presented to emergency departments in the United States. Surg Technol Int. 2017;31:352–8.
6. Chevinsky JD, Newman JM, Shah NV, Pancholi N, Holliman J, Sodhi N, Eldib A, Naziri Q, Zikria BA, Reilly JP, Barbash SE, Urban WP. Trends and epidemiology of tennis-related sprains/strains in the United States, 2010 to 2016. Surg Technol Int. 2017;31:333–8.
7. Dakic JG, Smith B, Gosling CM, Perraton LG. Musculoskeletal injury profiles in professional Women's tennis association players. Br J Sports Med. 2018;52(11):723–9. https://doi.org/10.1136/bjsports-2017-097865.
8. Gaw CE, Chounthirath T, Smith GA. Tennis-related injuries treated in United States emergency departments, 1990 to 2011. Clin J Sport Med. 2014;24(3):226–32.
9. Barber-Westin S, Noyes FR. Sports-specific programs for soccer, basketball, volleyball, and tennis. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete. 2nd ed. Berlin, New York: Springer-Verlag, Heidelberg; 2018. p. 377–425. https://doi.org/10.1007/978-3-662-56558-2_18.
10. Heckmann TP, Barber-Westin SD, Noyes FR. Rehabilitation of medial ligament injuries. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 636–52. https://doi.org/10.1016/b978-0-323-32903-3.00020-2.
11. Heckmann TP, Noyes FR, Barber-Westin SD. Rehabilitation of meniscus repair and transplantation procedures. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 760–71. https://doi.org/10.1016/b978-0-323-32903-3.00025-1.

12. Noyes FR, Barber-Westin SD, Heckmann TP. Rehabilitation of posterior cruciate ligament and posterolateral reconstructive procedures. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 578–606. https://doi.org/10.1016/b978-0-323-32903-3.00018-4.
13. Noyes FR, Heckmann TP, Barber-Westin SD. Rehabilitation after tibial and femoral osteotomy. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 858–67. https://doi.org/10.1016/b978-0-323-32903-3.00028-7.
14. Noyes FR, Barber-Westin SD. Operative options for extensor mechanism malalignment and patellar dislocation. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 970–1013. https://doi.org/10.1016/b978-0-323-32903-3.00035-4.
15. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med. 1991;19(5):513–8.
16. Girard O, Millet GP. Physical determinants of tennis performance in competitive teenage players. J Strength Cond Res. 2009;23(6):1867–72. https://doi.org/10.1519/JSC.0b013e3181b3df89.
17. Ulbricht A, Fernandez-Fernandez J, Ferrauti A. Conception for fitness testing and individualized training programs in the German tennis federation. Sport-Orthopädie-Sport-Traumatologie-Sports Orthop Traumatol. 2013;29(3):180–92.
18. Ellenbecker TS, Roetert EP, Sueyoshi T, Riewald S. A descriptive profile of age-specific knee extension flexion strength in elite junior tennis players. Br J Sports Med. 2007;41(11):728–32.
19. Borms D, Maenhout A, Cools AM. Upper quadrant field tests and isokinetic upper limb strength in overhead athletes. J Athl Train. 2016;51(10):789–96. https://doi.org/10.4085/1062-6050-51.12.06.
20. Ellenbecker TS, Roetert EP. An isokinetic profile of trunk rotation strength in elite tennis players. Med Sci Sports Exerc. 2004;36(11):1959–63.
21. Barber-Westin SD, Hermeto AA, Noyes FR. A six-week neuromuscular training program for competitive junior tennis players. J Strength Cond Res. 2010;24(9):2372–82. https://doi.org/10.1519/JSC.0b013e3181e8a47f.
22. Kumar S. Relationship between physical characteristics and ranking of young tennis players. Int J Phy Educ Sports Health. 2017;4(1):60–4.
23. Cooke K, Quinn A, Sibte N. Testing speed and agility in elite tennis players. Strength Cond J. 2011;33(4):69–72.
24. Leger LA, Lambert J. A maximal multistage 20-m shuttle run test to predict VO_2 max. Eur J Appl Physiol Occup Physiol. 1982;49(1):1–12.
25. Eriksson A, Johansson FR, Back M. Reliability and criterion-related validity of the 20-yard shuttle test in competitive junior tennis players. Open Access J Sports Med. 2015;6:269–76. https://doi.org/10.2147/OAJSM.S86442.
26. Girard O, Chevalier R, Leveque F, Micallef JP, Millet GP. Specific incremental field test for aerobic fitness in tennis. Br J Sports Med. 2006;40(9):791–6.
27. Ferrauti A, Kinner V, Fernandez-Fernandez J. The hit & turn tennis test: an acoustically controlled endurance test for tennis players. J Sports Sci. 2011;29(5):485–94. https://doi.org/10.1080/02640414.2010.539247.
28. Brechbuhl C, Girard O, Millet GP, Schmitt L. On the use of a test to exhaustion specific to tennis (TEST) with ball hitting by elite players. PLoS One. 2016;11(4):e0152389. https://doi.org/10.1371/journal.pone.0152389.
29. Fargeas-Gluck MA, Leger LA. Comparison of two aerobic field tests in young tennis players. J Strength Cond Res. 2012;26(11):3036–42. https://doi.org/10.1519/JSC.0b013e3182472fc3.
30. Fernandez-Fernandez J, Zimek R, Wiewelhove T, Ferrauti A. High-intensity interval training vs. repeated-sprint training in tennis. J Strength Cond Res. 2012;26(1):53–62. https://doi.org/10.1519/JSC.0b013e318220b4ff.
31. Ulbricht A, Fernandez-Fernandez J, Mendez-Villanueva A, Ferrauti A. Impact of fitness characteristics on tennis performance in elite junior tennis players. J Strength Cond Res. 2016;30(4):989–98. https://doi.org/10.1519/JSC.0000000000001267.
32. Myburgh GK, Cumming SP, Silva MCE, Cooke K, Malina RM. Maturity-associated variation in functional characteristics of elite youth tennis players. Pediatr Exerc Sci. 2016;28(4):542–52.
33. Kramer T, Huijgen BC, Elferink-Gemser MT, Visscher C. A longitudinal study of physical fitness in elite junior tennis players. Pediatr Exerc Sci. 2016;28(4):553–64.
34. Kramer T, Huijgen BC, Elferink-Gemser MT, Visscher C. Prediction of tennis performance in junior elite tennis players. J Sports Sci Med. 2017;16(1):14.
35. Munivrana G, Filipcic A, Filipcic T. Relationship of speed, agility, neuromuscular power, and selected anthropometrical variables and performance results of male and female junior tennis players. Coll Antropol. 2015;39(Suppl 1):109–16.
36. Barber-Westin SD, Hermeto A, Noyes FR. A six-week neuromuscular and performance training program improves speed, agility, dynamic balance, and core endurance in junior tennis players. J Athl Enhanc. 2015;4(1) https://doi.org/10.4172/2324-9080.1000185.
37. Florida U. Tournament levels. 2019. https://www.ustaflorida.com/youth-tennis/junior-tournaments/. Accessed Jan. 3 2019.
38. Fernandez-Fernandez J, Sanz-Rivas D, Kovacs MS, Moya M. In-season effect of a combined repeated sprint and explosive strength training program on

elite junior tennis players. J Strength Cond Res. 2015;29(2):351–7.
39. Fernandez-Fernandez J, Saez de Villarreal E, Sanz-Rivas D, Moya M. The effects of 8-week plyometric training on physical performance in Young tennis players. Pediatr Exerc Sci. 2016;28(1):77–86. https://doi.org/10.1123/pes.2015-0019.
40. Fernandez-Fernandez J, Sanz D, Sarabia JM, Moya M. The effects of sport-specific drills training or high-intensity interval training in Young tennis players. Int J Sports Physiol Perform. 2017;12(1):90–8. https://doi.org/10.1123/ijspp.2015-0684.
41. Kovacs MS. Movement for tennis: the importance of lateral training. Strength Cond J. 2009;31(4):77–85.
42. Kovacs MS, Roetert EP, Ellenbecker TS. Efficient deceleration: the forgotten factor in tennis-specific training. Strength Cond J. 2008;30(6):58–69.
43. Myers NL, Sciascia AD, Kibler WB, Uhl TL. Volume-based interval training program for elite tennis players. Sports Health. 2016;8(6):536–40.
44. Ochi S, Campbell MJ. The progressive physical development of a high-performance tennis player. Strength Cond J. 2009;31(4):59–68.
45. Reid M, Quinlan G, Kearney S, Jones D. Planning and periodization for the elite junior tennis player. Strength Cond J. 2009;31(4):69–76.
46. Reid M, Schneiker K. Strength and conditioning in tennis: current research and practice. J Sci Med Sport. 2008;11(3):248–56.
47. Roetert EP, Kovacs M, Knudson D, Groppel JL. Biomechanics of the tennis groundstrokes: implications for strength training. Strength Cond J. 2009;31(4):41–9.
48. Roetert EP, Ellenbecker TS, Reid M. Biomechanics of the tennis serve: implications for strength training. Strength Cond J. 2009;31(4):35–40.
49. Kovacs M, Roetert EP, Ellenbecker T. Complete conditioning for tennis. 2nd ed. Champaign, IL: Human Kinetics; 2016.
50. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lazaro-Haro C, Cugat R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: mechanisms of injury and underlying risk factors. Knee Surg Sports Traumatol Arthrosc. 2009;17(7):705–29. https://doi.org/10.1007/s00167-009-0813-1.
51. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engebretsen L, Bahr R, Krosshaug T. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. Am J Sports Med. 2010;38(11):2218–25. https://doi.org/10.1177/0363546510373570.
52. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lazaro-Haro C, Cugat R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. Knee Surg Sports Traumatol Arthrosc. 2009;17(8):859–79. https://doi.org/10.1007/s00167-009-0823-z.
53. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ, Russo KA. The effect of technique change on knee loads during sidestep cutting. Med Sci Sports Exerc. 2007;39(10):1765–73. https://doi.org/10.1249/mss.0b013e31812f56d1.
54. McNair PJ, Prapavessis H, Callender K. Decreasing landing forces: effect of instruction. Br J Sports Med. 2000;34(4):293–6.
55. Onate JA, Guskiewicz KM, Sullivan RJ. Augmented feedback reduces jump landing forces. J Orthop Sports Phys Ther. 2001;31(9):511–7.
56. Onate JA, Guskiewicz KM, Marshall SW, Giuliani C, Yu B, Garrett WE. Instruction of jump-landing technique using videotape feedback: altering lower extremity motion patterns. Am J Sports Med. 2005;33(6):831–42.
57. Wilderman DR, Ross SE, Padua DA. Thigh muscle activity, knee motion, and impact force during sidestep pivoting in agility-trained female basketball players. J Athl Train. 2009;44(1):14–25.
58. Zebis MK, Bencke J, Andersen LL, Dossing S, Alkjaer T, Magnusson SP, Kjaer M, Aagaard P. The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. Clin J Sport Med. 2008;18(4):329–37. https://doi.org/10.1097/JSM.0b013e31817f3e35.
59. Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, Kirkendall DT, Garrett W Jr. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med. 2005;33(7):1003–10. https://doi.org/10.1177/0363546504272261.
60. Foran B. High-performance sports conditioning. Champaign: Human Kinetics; 2001.
61. Barber-Westin SD, Noyes FR. Testing for neuromuscular problems and athletic performance. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete. Causes, impacts, and conditioning programs. 2nd ed. New York: Springer; 2017. p. 289–333.
62. Engelen-van Melick N, van Cingel RE, Tijssen MP, Nijhuis-van der Sanden MW. Assessment of functional performance after anterior cruciate ligament reconstruction: a systematic review of measurement procedures. Knee Surg Sports Traumatol Arthrosc. 2013;21(4):869–79. https://doi.org/10.1007/s00167-012-2030-6.
63. Hegedus EJ, McDonough SM, Bleakley C, Baxter D, Cook CE. Clinician-friendly lower extremity physical performance tests in athletes: a systematic review of measurement properties and correlation with injury. Part 2-the tests for the hip, thigh, foot and ankle including the star excursion balance test. Br J Sports Med. 2015;49(10):649–56. https://doi.org/10.1136/bjsports-2014-094341.
64. Kroman SL, Roos EM, Bennell KL, Hinman RS, Dobson F. Measurement properties of performance-

based outcome measures to assess physical function in young and middle-aged people known to be at high risk of hip and/or knee osteoarthritis: a systematic review. Osteoarthr Cartil. 2014;22(1):26–39. https://doi.org/10.1016/j.joca.2013.10.021.

65. Logerstedt D, Grindem H, Lynch A, Eitzen I, Engebretsen L, Risberg MA, Axe MJ, Snyder-Mackler L. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo ACL cohort study. Am J Sports Med. 2012;40(10):2348–56. https://doi.org/10.1177/0363546512457551.
66. Meierbachtol A, Rohman E, Paur E, Bottoms J, Tompkins M. Quantitative improvements in hop test scores after a 6-week neuromuscular training program. Sports Health. 2016;9(1):22–9. https://doi.org/10.1177/1941738116667933.
67. Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. Clin Orthop Relat Res. 1990;(255):204–14.
68. Barber-Westin SD, Noyes FR. Decreasing the risk of anterior cruciate ligament injuries in female athletes. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 373–404.
69. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. Phys Ther. 2007;87(3):337–49.
70. Gustavsson A, Neeter C, Thomee P, Silbernagel KG, Augustsson J, Thomee R, Karlsson J. A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2006;14(8):778–88. https://doi.org/10.1007/s00167-006-0045-6.
71. Greenberger HB, Paterno MV. Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. J Orthop Sports Phys Ther. 1995;22(5):202–6.
72. Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. J Orthop Sports Phys Ther. 1994;20(2):60–73.
73. Xergia SA, Pappas E, Georgoulis AD. Association of the single-limb hop test with isokinetic, kinematic, and kinetic asymmetries in patients after anterior cruciate ligament reconstruction. Sports Health. 2014;7(3):217–23. https://doi.org/10.1177/1941738114529532.
74. Ross MD, Langford B, Whelan PJ. Test-retest reliability of 4 single-leg horizontal hop tests. J Strength Cond Res. 2002;16(4):617–22.
75. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, Newton RU, Triplett NT, Dziados JE. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. J Appl Physiol. 1995;78(3):976–89.
76. Reiman MP, Manske RC. Functional testing in human performance. Champaign: Human Kinetics; 2009.
77. Benton MJ, Raab S, Waggener GT. Effect of training status on reliability of one repetition maximum testing in women. J Strength Cond Res. 2013;27(7):1885–90. https://doi.org/10.1519/JSC.0b013e3182752d4a.
78. Neto JC, Cedin L, Dato CC, Bertucci DR, Perez S, Baldissera V. A single session of testing for one repetition maximum (1RM) with either exercises is trustworthy. J Exerc Physiol Online. 2015;18(3):74–80.
79. Redden J, Stokes K, Williams S. Establishing the reliability and limits of meaningful change of lower limb strength and power measures during seated leg Press in Elite Soccer Players. J Sports Sci Med. 2018;17(4):539–46.
80. Seo DI, Kim E, Fahs CA, Rossow L, Young K, Ferguson SL, Thiebaud R, Sherk VD, Loenneke JP, Kim D, Lee MK, Choi KH, Bemben DA, Bemben MG, So WY. Reliability of the one-repetition maximum test based on muscle group and gender. J Sports Sci Med. 2012;11(2):221–5.
81. Kraemer WJ, Hakkinen K, Triplett-Mcbride NT, Fry AC, Koziris LP, Ratamess NA, Bauer JE, Volek JS, McConnell T, Newton RU, Gordon SE, Cummings D, Hauth J, Pullo F, Lynch JM, Fleck SJ, Mazzetti SA, Knuttgen HG. Physiological changes with periodized resistance training in women tennis players. Med Sci Sports Exerc. 2003;35(1):157–68.
82. Chimera NJ, Swanik KA, Swanik CB, Straub SJ. Effects of plyometric training on muscle-activation strategies and performance in female athletes. J Athl Train. 2004;39(1):24–31.
83. Young W, MacDonald C, Heggen T, Fitzpatrick J. An evaluation of the specificity, validity and reliability of jumping tests. J Sports Med Phys Fitness. 1997;37(4):240–5.
84. Bliss A, McCulloch H, Maxwell NS. The effects of an eight-week plyometric training program on golf swing performance characteristics in skilled adolescent golfers. Int J Golf Sci. 2015;4(2):120–35.
85. Jones MT, Lorenzo DC. Assessment of power, speed, and agility in athletic, preadolescent youth. J Sports Med Phys Fitness. 2013;53(6):693–700.
86. Lee C, Lee S, Yoo J. The effect of a complex training program on skating abilities in ice hockey players. J Phys Ther Sci. 2014;26(4):533–7. https://doi.org/10.1589/jpts.26.533.
87. Behringer M, Neuerburg S, Matthews M, Mester J. Effects of two different resistance-training programs on mean tennis-serve velocity in adolescents. Pediatr Exerc Sci. 2013;25(3):370–84.
88. Ikeda Y, Kijima K, Kawabata K, Fuchimoto T, Ito A. Relationship between side medicine-ball throw performance and physical ability for male and female athletes. Eur J Appl Physiol. 2007;99(1):47–55. https://doi.org/10.1007/s00421-006-0316-4.

89. Alaranta H, Hurri H, Heliovaara M, Soukka A, Harju R. Non-dynamometric trunk performance tests: reliability and normative data. Scand J Rehabil Med. 1994;26(4):211–5.
90. Harding VR, Williams AC, Richardson PH, Nicholas MK, Jackson JL, Richardson IH, Pither CE. The development of a battery of measures for assessing physical functioning of chronic pain patients. Pain. 1994;58(3):367–75.
91. Reid M, Sibte N, Clark S. Tennis players. In: Gore CJ, Tanner RK, editors. Physiological tests for elite athletes. 2nd ed. Champaign, IL: Human Kinetics; 2013. p. 449–61.
92. Knapik JJ, Sharp MA, Canham-Chervak M, Hauret K, Patton JF, Jones BH. Risk factors for training-related injuries among men and women in basic combat training. Med Sci Sports Exerc. 2001;33(6):946–54.
93. Roetert EP, Ellenbecker TS. Complete conditioning for tennis. Champaign, IL: Human Kinetics; 2007.
94. Ramsbottom R, Brewer J, Williams C. A progressive shuttle run test to estimate maximal oxygen uptake. Br J Sports Med. 1988;22(4):141–4.
95. Bianco A, Jemni M, Thomas E, Patti A, Paoli A, Roque J, Palma C, Tabacchi G. A systematic review to determine reliability and usefulness of the field-based test batteries for the assessment of physical fitness in adolescents – the ASSO project. Inj J Occup Med Envir Health. 2015;28(3):445–78.
96. Williford HN, Scharff-Olson M, Duey WJ, Pugh S, Barksdale JM. Physiological status and prediction of cardiovascular fitness in highly trained youth soccer athletes. J Strength Cond Res. 1999;13(1):10–5.
97. Gabbett TJ. A comparison of physiological and anthropometric characteristics among playing positions in junior rugby league players. Br J Sports Med. 2005;39(9):675–80.
98. Mayorga-Vega D, Aguilar-Soto P, Viciana J. Criterion-related validity of the 20-m shuttle run test for estimating cardiorespiratory fitness: a meta-analysis. J Sports Sci Med. 2015;14:536–47.
99. Bangsbo J, Iaia FM, Krustrup P. The Yo-Yo intermittent recovery test : a useful tool for evaluation of physical performance in intermittent sports. Sports Med (Auckland, NZ). 2008;38(1):37–51.
100. Hermassi S, Ingebrigtsen J, Schwesig R, Fieseler G, Delank K-S, Chamari K, Shephard RJ, Chelly M-S. Effects of in-season short-term aerobic and high-intensity interval training program on repeated sprint ability and jump performance in handball players. J Sports Med Phys Fitness. 2018;58(1-2):50–6.
101. Owen C, Jones P, Comfort P. The reliability of the submaximal version of the Yo-Yo intermittent recovery test in elite youth soccer. J Trainol. 2017;6(1):31–4.

Part V

Objective Testing

19 The Physician's Comprehensive Examination for Return to Sport

Frank R. Noyes and Sue Barber-Westin

19.1 Introduction

The decision of when to release an athlete to unrestricted sports activities after major knee surgery is based on many factors, including successful completion of advanced rehabilitation, psychological readiness, completion of advanced neuromuscular training programs appropriate for the desired sport, and a comprehensive examination by the physician. During rehabilitation, athletes are taken through a specific progression of exercises, with the athlete understanding and focusing on specific goals. In this manner, return to sport (RTS) is based on the athlete meeting all of the set goals and not simply a matter of the amount of time that has elapsed postoperatively.

At our center, physical therapists and athletic trainers involved in patient care are able to personally discuss RTS decisions with the treating orthopedic surgeon, which is especially advantageous for patients eager to expedite resumption of unrestricted activities. For surgical management teams that do not have the ability to communicate on a regular basis, there are standardized forms that facilitate examination findings. One valuable form is the International Knee Documentation Committee (IKDC) knee examination form, shown in Tables 19.1 and 19.2, with instructions provided in Table 19.3. This examination format documents knee range of motion (ROM) and effusion, stability of all knee ligaments, graft harvest site and compartment pain, joint space on X-rays, and findings from a single-leg hop test. In addition, observation is made of generalized ligament laxity, overall lower limb alignment, patella position, and patella subluxation or dislocation. At our center, many objective tests are conducted to determine muscle strength, dynamic lower limb alignment, and neuromuscular function (see Chaps. 20 and 21). Our comprehensive evaluation and criteria for RTS are summarized in Table 19.4.

The scientific basis for the examination and classification of knee ligament stability tests has been previously described in detail [1]. The classification system developed by the senior author and Edward Grood, PhD, derived from a series of biomechanical studies, is based on seven concepts:

(1) The final diagnosis of knee ligament injuries is based on the specific anatomic defect derived from the abnormal motion limits and joint subluxations.
(2) Ligaments have distinct mechanical functions to provide limits to tibiofemoral motions and the types of motions that occur between opposing cartilage surfaces.
(3) Although there are six degrees of freedom (DOF), the manual stress examinations are designed to test just one or two limits at a time (Fig. 19.1)

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_19

Table 19.1 IKDC knee examination criteria for ratings (knee ligament reconstruction)

	IKDC ratings			
	Normal	Nearly normal	Abnormal	Severely abnormal
Effusion	None	Mild	Moderate	Severe
Passive motion deficit				
Lack of extension	<3°	3–5°	6–10°	>10°
Lack of flexion	0–5°	6–15°	16–25°	>25°
Ligament examination (manual, instrumented, X-ray)				
Lachman (25° flexion, 134 N)	<3 mm	3–5 mm	6–10 mm	>10 mm
Lachman (25° flexion, manual maximum), anterior endpoint	<3 mm, firm	3–5 mm	6–10 mm, soft	>10 mm
Total anteroposterior translation (25° flexion)	< 3 mm	3–5 mm	6–10 mm	>10 mm
Total anteroposterior translation (70° flexion)	< 3 mm	3–5 mm	6–10 mm	>10 mm
Posterior drawer test (70° flexion)	<3 mm	3–5 mm	6–10 mm	>10 mm
Medial joint opening (20° flexion, valgus rotation)	<3 mm	3–5 mm	6–10 mm	>10 mm
Lateral joint opening (20° flexion, varus rotation)	<3 mm	3–5 mm	6–10 mm	> 10 mm
External rotation test (30° flexion prone)	<5°	6–10°	11–19°	>20°
External rotation test (90° flexion prone)	<5°	6–10°	11–19°	>20°
Pivot shift	Equal	+ glide	++ (clunk)	+++ (gross)
Reverse pivot shift	Equal	Glide	Gross	Marked
Compartment findings				
Crepitus anterior compartment	None	Moderate	Mild pain	> mild pain
Crepitus medial compartment	None	Moderate	Mild pain	> mild pain
Crepitus lateral compartment	None	Moderate	Mild pain	> mild pain
Harvest site pathology	None	Mild	Moderate	Severe
X-ray findings				
Medial joint space	None	Mild	Moderate	Severe
Lateral joint space	None	Mild	Moderate	Severe
Patellofemoral	None	Mild	Moderate	Severe
Anterior joint space (sagittal)	None	Mild	Moderate	Severe
Posterior joint space (sagittal)	None	Mild	Moderate	Severe
Functional test: one-leg hop (% of opposite side)	≥ 90%	89% to 76%	75% to 50%	<50%

IKDC International Knee Documentation Committee

Table 19.2 IKDC knee examination other variables assessed

<table>
<tr><th>Variable</th><th colspan="4">IKDC ratings</th></tr>
<tr><td>Generalized laxity</td><td>Tight</td><td>Normal</td><td colspan="2">Lax</td></tr>
<tr><td>Alignment</td><td>Obvious varus</td><td>Normal</td><td colspan="2">Obvious valgus</td></tr>
<tr><td>Patella position</td><td>Obvious baja</td><td>Normal</td><td colspan="2">Obvious alta</td></tr>
<tr><td>Patella subluxation/ dislocation</td><td>Centered</td><td>Subluxable</td><td>Subluxed</td><td>Dislocated</td></tr>
<tr><td rowspan="2">Range of motion (extension/ flexion)</td><td>Index side: passive ____/____/____</td><td>Index side: active ___/____/____</td><td colspan="2"></td></tr>
<tr><td>Opposite side: passive ___/____/____</td><td>Opposite side: active ___/____/____</td><td colspan="2"></td></tr>
</table>

IKDC International Knee Documentation Committee

Table 19.3 IKDC knee examination instructions

Variable	Instructions
Effusion	An effusion is assessed by ballotting the knee. A fluid wave (<25 cc) is graded mild, easily ballotable fluid is graded moderate (25–60 cc), and a tense knee secondary to effusion (>60 cc) is rated severe
Passive motion deficit	Passive range of motion is measured with a goniometer and recorded for the index side and opposite or normal side. Record values for zero point/hyperextension/flexion (e.g., 10° of hyperextension, 150° of flexion = 10/0/150; 10° of flexion to 150° of flexion = 0/10/150). Extension is compared to that of the normal knee
Ligament examination	The Lachman test, total AP translation at 70°, and medial and lateral joint opening may be assessed with manual, instrumented, or stress X-ray examination. Only one should be graded, preferably a "measured displacement." A force of 134 N (30 lbs) and the maximum manual are recorded in instrumented examination of both knees. Only the measured displacement at the standard force of 134 N is used for grading. The numerical values for the side to side difference are rounded off, and the appropriate box is marked. The end point is assessed in the Lachman test. The end point affects the grading when the index knee has 3–5 mm more anterior laxity than the normal knee. In this case, a soft end point results in an abnormal grade rather than a nearly normal grade The 70° posterior sag is estimated by comparing the profile of the injured knee to the normal knee and palpating the medial femoral tibial step-off. It may be confirmed by noting that contraction of the quadriceps pulls the tibia anteriorly The external rotation tests are performed with the patient prone and the knee flexed 30° and 70°. Equal external rotational torque is applied to both feet, and the degree of external rotation is recorded The pivot shift and reverse pivot shift are performed with the patient supine, with the hip in 10–20° of abduction and the tibia in neutral rotation using either the Losee, Noyes, or Jakob techniques. The greatest subluxation, compared to the normal knee, should be recorded
Compartment findings	Patellofemoral crepitation is elicited by extension against slight resistance. Medial and lateral compartment crepitation is elicited by extending the knee from a flexed position with a varus stress and then a valgus stress (i.e., McMurray test). Grading is based on intensity and pain
Harvest site pathology	Note tenderness, irritation, or numbness at the autograft harvest site
X-ray findings	A bilateral, double leg PA weight-bearing roentgenogram at 35–45° of flexion (tunnel view) is used to evaluate narrowing of the medial and lateral joint spaces. The Merchant view at 45° is used to document patellofemoral narrowing. A mild grade indicates minimal changes (i.e., small osteophytes, slight sclerosis or flattening of the femoral condyle) and narrowing of the joint space which is just detectable. A moderate grade may have those changes and joint space narrowing (e.g., a joint space of 2–4 mm side or up to 50% joint space narrowing). Severe changes include a joint space of less than 2 mm or >50% joint space narrowing
Functional test	The patient is asked to perform a one-leg hop for distance on the index and normal side. Three trials for each leg are recorded and averaged. A ratio of the index to normal knee is calculated

AP anteroposterior, *IKDC* International Knee Documentation Committee, *PA* posteroanterior

Table 19.4 Noyes Knee Institute criteria for RTS after major knee surgery

Test	Criteria for RTS
Knee ligament tests	
Lachman and pivot shift (ACL reconstructions)	IKDC normal or nearly normal
KT-2000 (ACL reconstructions)	≤ 3 mm increase over opposite normal knee
Posterior drawer (PCL reconstructions)	IKDC normal or nearly normal
Lateral joint opening (LCL or posterolateral reconstructions)	IKDC normal or nearly normal
External tibial rotation (LCL or posterolateral reconstructions)	IKDC normal or nearly normal
Medial joint opening (MCL reconstructions)	IKDC normal or nearly normal
Range of knee motion	IKDC normal or nearly normal
Knee joint effusion	None

(continued)

Table 19.4 (continued)

Test	Criteria for RTS
Patellar tests	
Compression pain	None
Crepitus	None or mild
Lateral subluxation	None or mild
Medial subluxation	None or mild
Tibiofemoral tests	
Medial joint pain	None
Lateral joint pain	None
Meniscus-related pain on palpation, forced flexion	None
McMurray test	Negative
Gait analysis (observational)	Symmetrical, no limp, no hyperextension
X-rays	Complete healing osteotomy site, normal alignment, IKDC normal or nearly normal rating joint space, normal position TKA/PFA/UKA prosthesis
Quadriceps and hamstrings muscle strength tests (in order of preference)	
Isokinetic evaluation 180°/s and 300°/s	≤10% deficit compared with opposite side
Isometric evaluation (60° flexion quadriceps, 60° or 90° hamstrings, average of 3 repetitions)	≤10% deficit compared with opposite side
1-repetition maximum bench press and leg press	≤10% deficit compared with opposite side
Single-leg hop tests	
Select any 2: Single hop, triple hop, triple crossover hop, timed hop	≤15% deficit compared with opposite side
Single-leg squat test (5 repetitions)	No knee valgus, medial-lateral movement, or pelvic tilt
Video drop-jump test	
Software available	≥60% normalized knee separation distance
No software available	No valgus, knees/ankles aligned with hips, knees flexed on controlled landing
Vertical jump test	
1-legged	≤10% deficit
2-legged	≥14 inches (35.5 cm)
Core strength measure (i.e., 60-second sit-up test)	Published standards
Video plant and cut drill (optional)	High hip and knee flexion, upright posture, no valgus collapse
Multi-stage fitness test (optional)	Published standards
ACL-RSI questions	
Are you confident that you can perform at your previous level of sports participation?	Yes
Are you nervous about playing your sport?	No
Are you fearful of reinjuring your knee by playing your sport?	No

ACL anterior cruciate ligament, *ACL-RSI* anterior cruciate ligament return to sport after injury scale, *IKDC* International Knee Documentation Committee, *KT-2000* knee arthrometer, *LCL* lateral collateral ligament, *MCL* medial collateral ligament, *PCL* posterior cruciate ligament, *PFA* patellofemoral arthroplasty, *RTS* return to sport, *TKA* total knee arthroplasty, *UKA* unicompartmental knee arthroplasty

(4) Ultimately, the clinical examination must be analyzed by a six-DOF system to detect abnormalities.
(5) Together, the ligaments and joint geometry provide two limits (opposite directions) for each DOF.
(6) Rotatory subluxations are characterized by the separate compartment translations that occur to the medial and lateral tibial plateaus during the clinical test.
(7) The damage to each ligament and capsular structure is diagnosed using tests in which the primary and secondary ligament restraints have been experimentally determined [3].

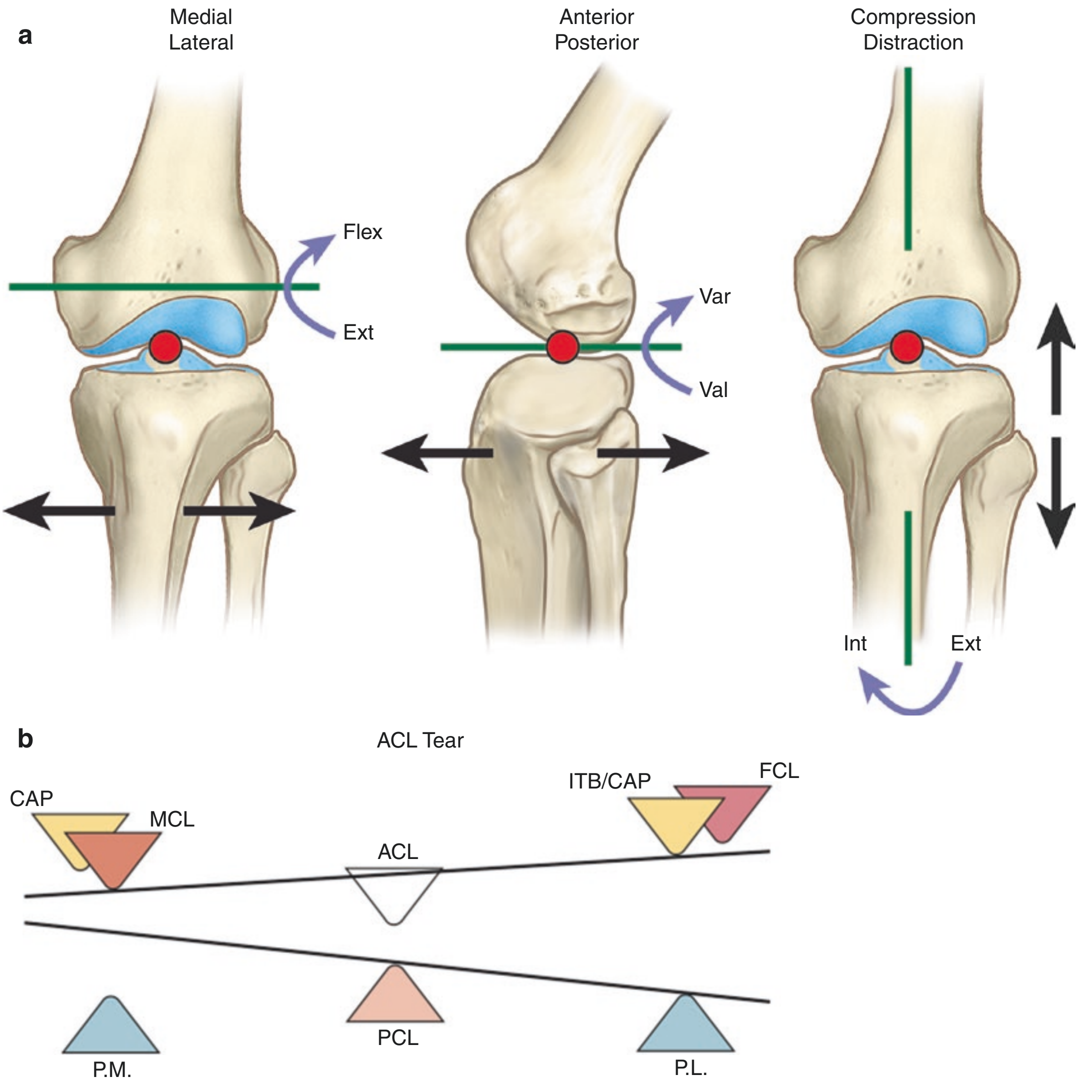


Fig. 19.1 (**a**) The knee joint has three axes of motion: flexion-extension, varus-valgus, and internal-external rotation. About each axis is a rotation and translation. The physical examination isolates each of the rotations and translations and compares normal with abnormal (after injury) based on known biomechanical data as to which ligaments are resisting the motion. (**b**) A "bumper model" of the knee joint is shown. The medial tibiofemoral and lateral tibiofemoral compartments show anterior-posterior translations due to the effect of the combined motions. Rotational stability is defined by tibiofemoral compartment translations that represent the final position or subluxation of each tibiofemoral compartment. The figure shows the result of an ACL tear in which the central bumper is lost. In the pivot shift test, the resulting lateral compartment anterior translation is resisted by secondary restraints represented by the iliotibial band (ITB) and anterolateral capsule. If these structures are lax, the fibular collateral ligament (FCL) will be a final resisting structure. *CAP* capsule, *MCL* medial collateral ligament, *ACL* anterior cruciate ligament, *PCL* posterior cruciate ligament, *PM* posteromedial, *PL* posterolateral (**b**, reprinted from Noyes and Barber-Westin [2])

Patients who have undergone reconstruction to the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), lateral collateral ligament (LCL, also known as the fibular collateral ligament), and/or posterolateral structures undergo manual tests, knee arthrometer testing (KT-2000), and stress radiographs (if necessary) as a portion of the comprehensive examination to determine the integrity of the reconstructed ligament(s).

Matheson et al. [4] identified the multiple factors that go into the RTS decision process, including nonmedical factors, such as a team's need for a skilled player or the athlete's strong motivation to return prematurely for economic or psychological reasons; pressure from coaches, school administrators, parents, and peers to return before the injury has completely resolved; potential legal liability issues for the physician for aggravated injury; and ethical issues regarding the risks of reinjury to the athlete. Conversely, it is crucial to identify and address patient fears, anxieties, and other psychological issues (such as an eating or sleeping disorder). The role of the team physician is discussed in detail in Chap. 5.

19.2 Radiographs

If radiographs have not been obtained postoperatively, or if there is any question regarding the healing ligament, prosthesis, hardware position, or joint space in the tibiofemoral or patellofemoral compartments, it is required that appropriate views should be ordered. These may include standing anteroposterior (AP) at 0° flexion, lateral at 30° flexion, weight-bearing posteroanterior (PA) at 45° flexion (Fig. 19.2), and patellofemoral axial views. Double-stance full-standing radiographs of both lower extremities, from the femoral heads to the ankle joints, are obtained in patients who underwent high tibial osteotomy or distal femoral osteotomy. The mechanical axis and weight-bearing line are measured as described elsewhere [5]. Osseous healing, prosthesis position (for total knee arthroplasty, patellofemoral arthroplasty, and unicompartmental knee arthroplasty) (Fig. 19.3), and joint space are all evaluated as required.

In knees that have undergone PCL reconstruction, stress radiography may be performed if there is a question of the status of the graft (Fig. 19.4) [7]. The radiograph should be as close to a pure lateral as possible, with the two femoral condyles superimposed on themselves. A horizontal line is placed across the medial tibial plateau, and a perpendicular line determines the posterior position of each femoral condyle. A similar measurement is made for the most posterior position of the medial and lateral tibial plateau. The amount of tibial translation is the average of both of these measurements. An alternative technique is to measure the posterior extent of the Blumensaat line and the proximal aspect of the PCL tibial fossa, which avoids the error of tibial rotation. There is an alternative method of a lateral kneeling view of the operative and contralateral knee joint.

Fig. 19.2 Anteroposterior radiograph of a 26-year-old female after ACL revision surgery. The patient had a prior vertical graft placement that required a staged bone grafting of tibial and femoral tunnels. A two-incision technique was used, with an accessory lateral incision for an anatomic anteromedial bundle bone-patellar tendon-bone ACL autograft revision reconstruction

Medial stress radiographs may be obtained in patients who have had an MCL injury or reconstruction. The radiograph is taken at 20° of flexion in neutral tibial rotation with a 67-N valgus force applied. The difference in millimeters of

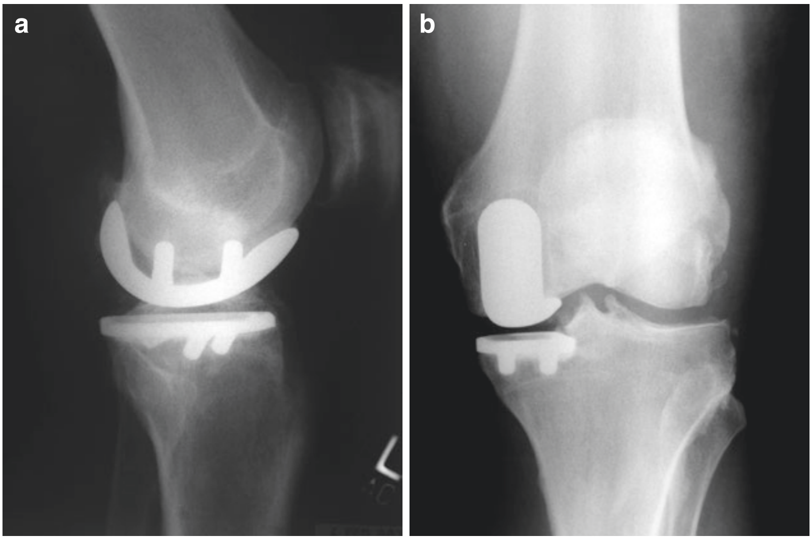


Fig. 19.3 Postoperative (**a**) lateral and (**b**) anteroposterior radiographs after a lateral unicompartmental knee arthroplasty show excellent position of the prosthesis (Reprinted from Noyes and Barber-Westin [6])

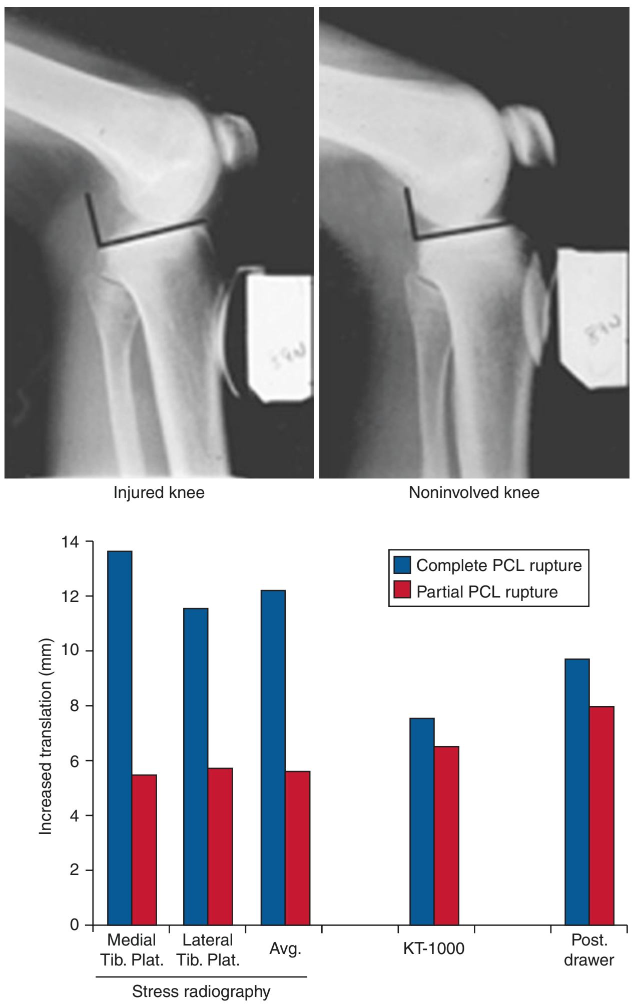


Fig. 19.4 The results of lateral stress radiography on 20 patients with PCL deficiency (9 complete ruptures and 11 partial ruptures). The differences in the measurements between complete and partial PCL ruptures for the medial tibial plateau (Tib. Plat.), the lateral tibial plateau, and the average of both plateaus were statistically significant ($P < 0.01$). Differences in the KT-1000 and posterior (Post.) drawer measurements between complete and partial PCL ruptures were not significant. The KT measurements at 70° of flexion underestimated the magnitude of posterior tibial subluxation for complete PCL ruptures (Reprinted from Noyes and Barber-Westin [7])

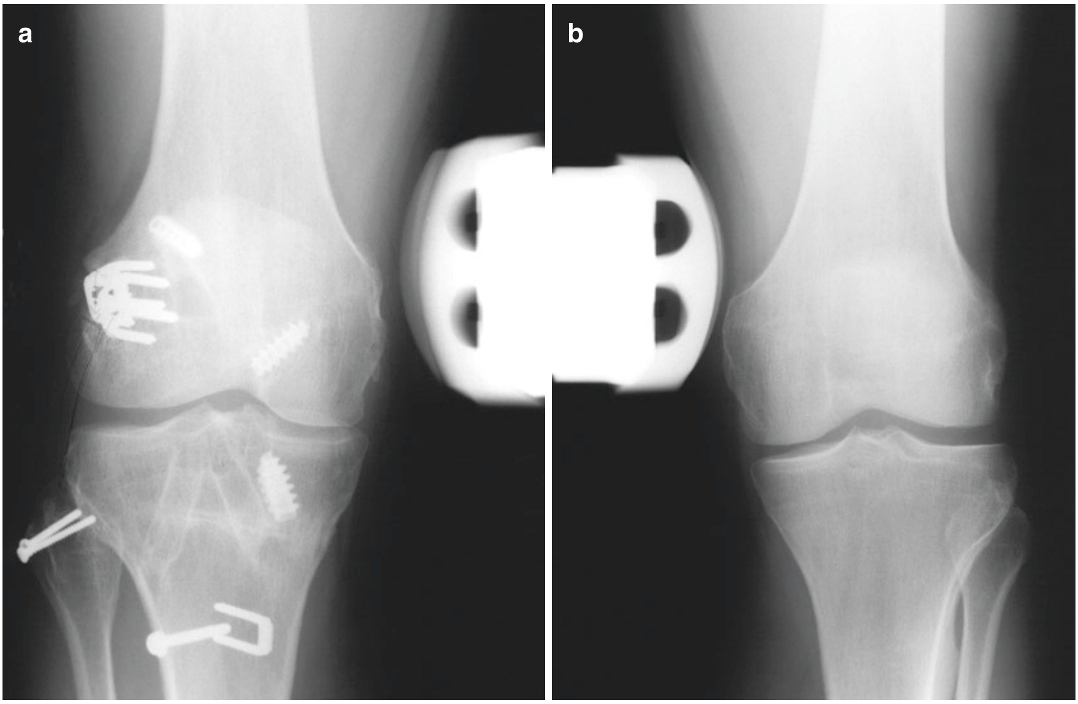


Fig. 19.5 (**a**) Postoperative lateral stress radiographs in a patient that underwent an ACL reconstruction and an LCL reconstruction show no increase in lateral tibiofemoral joint opening compared with the (**b**) contralateral normal knee (Reprinted from Noyes and Barber-Westin [8])

medial tibiofemoral compartment opening between knees is documented. Lateral stress radiographs may be required (20° flexion, neutral tibial rotation, 67-N varus force) in knees that had an LCL injury or reconstruction to evaluate lateral joint opening as a measure of successful lateral reconstruction (Fig. 19.5).

19.3 Range of Knee Motion, Muscle Strength, and Gait

Passive ROM is measured with a goniometer and recorded for both knees. The values are recorded for zero point/hyperextension/flexion (e.g., 10° of hyperextension, 150° of flexion = 10/0/150; 10° of flexion to 150° of flexion = 0/10/150). The centimeters of heel height may be measured to compare knee hyperextension between limbs. ROM should be normal or nearly normal according to IKDC standards for RTS. Manual assessment of the strength of the quadriceps, hamstrings, and hip musculature may be done; however, the more critical isokinetic muscle testing done previously by the therapy staff is reviewed by the physician. The patient must demonstrate no more than a 10% deficit in quadriceps and hamstrings peak torque compared with the opposite knee at 180°/s and 300°/s to return to unrestricted activities (see also Chap. 21). The patient's gait is assessed and must be symmetrical, with no abnormalities, knee hyperextension, or Trendelenburg sign.

19.4 Patellofemoral Examination

The patellofemoral joint examination is performed with the patient in the standing, sitting, and supine positions. In a standing position, the "squinting" or inward femoral rotation of the patella is an indication of increased hip anteversion and abnormal femoral internal rotation (Fig. 19.6). In these cases, an increase in the Q-angle is obvious due to compensatory external tibial rotation. Hip internal and external rotation

Fig. 19.6 Standing rotational malalignment shows "squinting patella" and the "miserable malalignment syndrome" (Reprinted from Noyes and Barber-Westin [9])

Fig. 19.7 Supine external-internal hip rotation abnormality (Reprinted from Reprinted from Noyes and Barber-Westin [9])

is measured in the prone position (Fig. 19.7). With the patient seated and the knee at 90°, active extension is performed to detect a lateral extension subluxation J-sign which often occurs with patella alta and confirms the necessity of measurement of patellar height on lateral radiographs (Fig. 19.8).

Palpation of parapatellar soft tissues and the fat pad is performed for swelling and elicitation of pain (Fig. 19.9). Often, the medial and lateral fat pads are visibly enlarged and tender as a joint reactive inflammation when associated extensor mechanism malalignment and lateral patellar subluxation are present. The determination of patellofemoral articular cartilage damage is difficult, and sophisticated magnetic resonance imaging (MRI) studies with T-2 generation imaging are helpful. The patellar compression test should be performed with flexion and extension of the knee to evaluate for articular crepitus or pain as an indication of cartilage abnormalities. The stabilizing restraints of the medial patellofemoral ligament and medial and lateral retinaculum soft tissue restraints are tested by passive patellar translation tests (patellar glide at 0° and 30° flexion) in medial and lateral directions, with patellar mobility noted (Figs. 19.10 and 19.11). Normally, there is a passive 10 mm of medial glide indicating no abnormal tightness of the lateral retinaculum. In some instances, there is a complete lack of medial glide due to abnormal shortening and tightness of the lateral

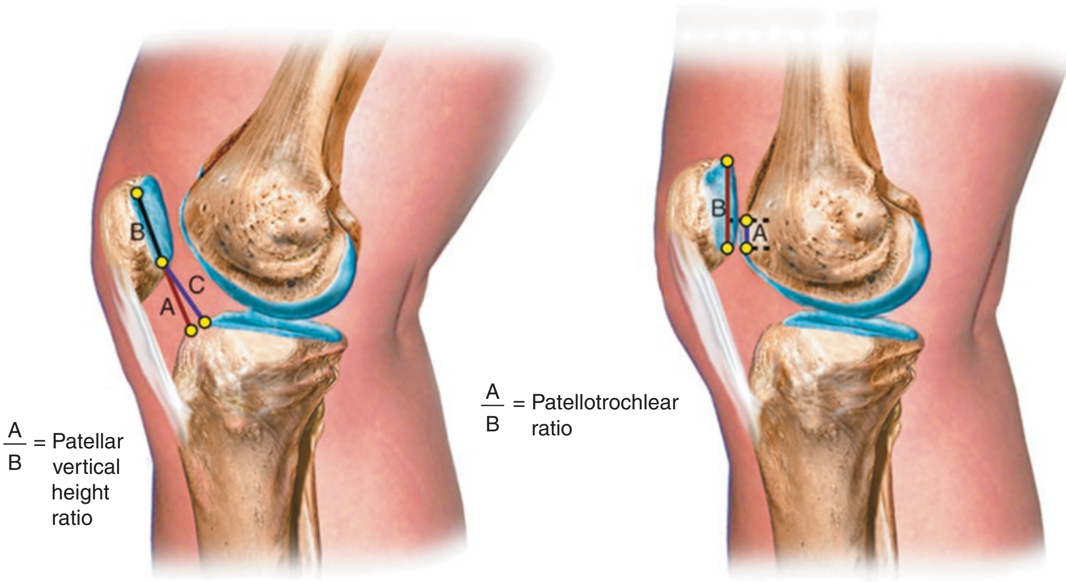


Fig. 19.8 (*Left*) Method used to determine patellar vertical height ratio on lateral radiograph with a quadriceps contraction to show the maximum elevated position of the patella. The numerator, line segment A, is the distance between the most ventral (anterosuperior) rim of the tibial plateau and the lowest end of the patellar articular surface. The denominator, line segment B, is the maximum length of the patellar articular surface. An alternative numerator, line segment C, locates the tibial reference point on the middle of the tibial plateau. The patellar vertical height ratio equals A/B or C/B. (*Right*) Alternative patellotrochlear ratio measurement. The mean ratio is 32 ± 12%; >50% indicates patella infera, and <12% indicates patella alta (Reprinted from Reprinted from Noyes and Barber-Westin [9])

Fig. 19.9 Palpation of parapatellar soft tissues and the fat pad is performed for swelling and elicitation of pain (Reprinted from Noyes and Barber-Westin [8])

retinaculum. Radiographs will show a lateral patellar tilt consistent with a lateral patellar contracture syndrome. A passive medial glide that is greater than two patellar quadrants (over 50% of patella width) indicates abnormal laxity of the medial restraining soft tissues. A return of normal patellofemoral function and stability, along with proper quadriceps control, is an absolute requirement for successful RTS. Patients are counseled of the potential for the onset of patellar pain with resumption of full activities and educated regarding appropriate management if discomfort or a noticeable increase in crepitus occurs.

Fig. 19.10 Patellofemoral joint examination. (**a**) Lateral tibial patellar tendon attachment full extension. (**b**) Normal lateral glide 30° flexion. Manual medial glide at (**c**) 0° and (**d**) 30° flexion (Reprinted from Reprinted from Noyes and Barber-Westin [9])

Fig. 19.11 Restoration of full knee motion and normal patellar mobility after an MPFL reconstruction. (From Noyes and Albright [10])

19.5 Meniscus Tests

Patients who had a concomitant meniscus tear requiring repair or partial meniscectomy are examined to determine if residual tibiofemoral compartment pain exists. The presence of tibiofemoral joint line pain on joint palpation is a primary indicator of a repeat meniscus tear. Other clinical signs include pain on forced flexion, obvious meniscal displacement during joint compression and flexion and extension, lack of full extension, and a positive McMurray test [11, 12]. The clinical examination should assess for tenderness on palpation at the posterolateral aspect of the joint at the anatomic site of the popliteomeniscal attachments that may have been disrupted producing abnormal meniscus subluxation of the posterior lateral meniscus. In such cases, the MRI is frequently negative. The McMurray test is performed in maximum flexion, progressing from maximum external rotation to internal rotation and then back to external rotation. This test may produce a lateral palpable snapping sensation, representing an anterior subluxation of the posterior horn of the lateral meniscus with maximum internal rotation. The presence of moderate or severe tibiofemoral compartment pain believed related to a repeat meniscus tear or failure of a meniscus repair may contraindicate release to unrestricted activities. MRI may be recommended to determine the status of the menisci, especially in a younger athlete in whom preservation of this structure is paramount [13].

19.6 Knee Ligament Tests

19.6.1 Anterior Cruciate Ligament

Patients who underwent ACL reconstruction undergo Lachman (Fig. 19.12), flexion-rotation drawer, and pivot shift testing (Fig. 19.13). KT-2000 testing is performed by the therapist at 134 N to determine total AP displacement. The Lachman test is graded according to IKDC ratings (Table 19.1). The pivot shift test is recorded on a scale of 0 to III, with a grade of 0 indicating no pivot shift (IKDC grade normal); grade I, a slip or glide (IKDC grade nearly normal); grade II, a jerk with gross subluxation or clunk (IKDC grade abnormal); and grade III, gross subluxation with impingement of the posterior aspect of the lateral side of the tibial plateau against the femoral condyle (IKDC grade severely abnormal). Unfortunately, these tests are qualitative and highly dependent on the examiner's skill and experience. The use of a KT-2000 or other objective measuring instrument of anterior tibial translation is recommended. Patients with <3 mm of anterior tibial translation should have a negative pivot shift test, assuming the ACL graft is in an anatomic location. In Fig. 19.14, the abnormal subluxations of the lateral and medial tibia plateau are shown; during the pivot shift test, the examiner should visually gauge the subluxation of both tibiofemoral compartments. Note that the center of tibial rotation shifts medially outside the knee joint, which is controlled in part by the functional restraint of the MCL. With injury to the secondary lateral restraints (iliotibial band and anterolateral ligament), there is increased tibial subluxation, indicating a grade III pivot shift.

Fig. 19.12 Lachman test (Reprinted from Noyes and Barber-Westin [14])

Patients that demonstrate a grade II or III pivot shift and>5 mm of increase in Lachman testing are counseled on the potential need for revision ACL reconstruction. Those who wish to resume high-risk sports are warned of the potential for

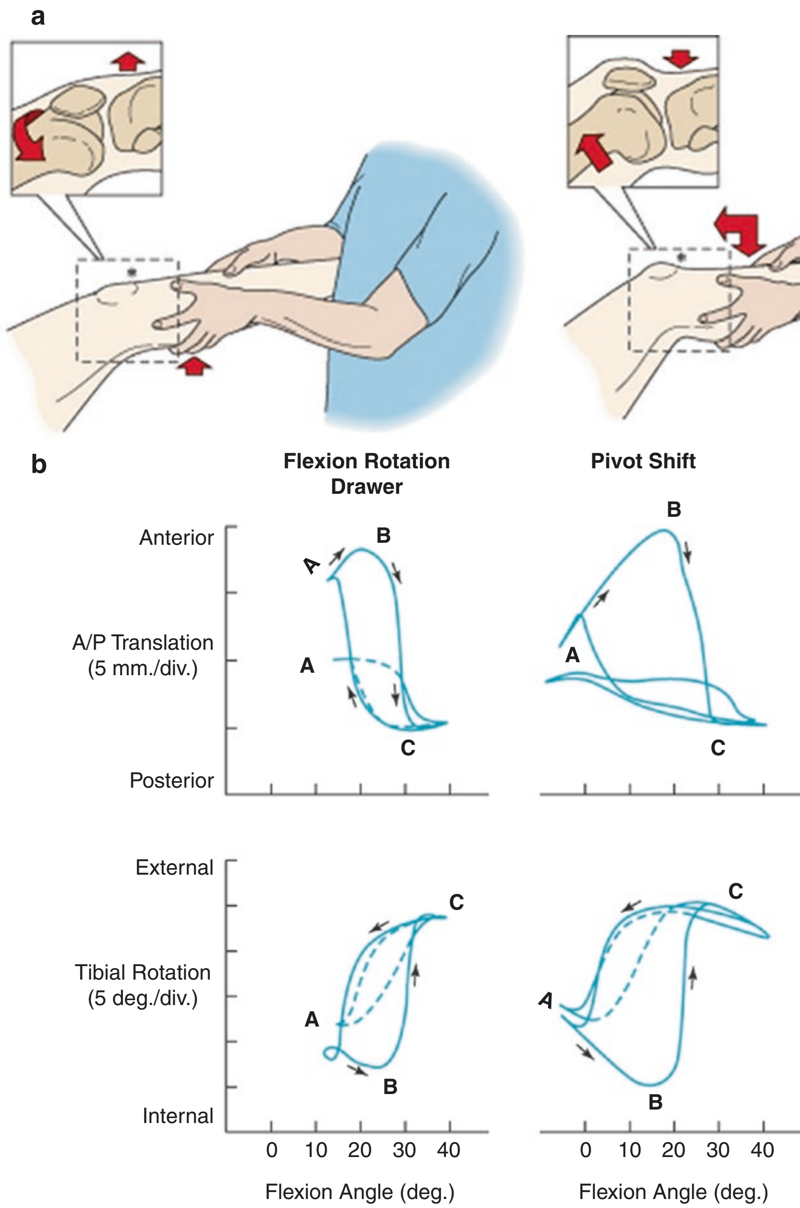


Fig. 19.13 Flexion-rotation drawer and pivot shift tests. (**a**) With the leg held in neutral rotation, the weight of the thigh causes the femur to drop back posteriorly and rotate externally, producing anterior subluxation of the tibial plateau. Gentle flexion and a downward push on the leg reduce the subluxation. This test allows the coupled motion of anterior translation-internal rotation to produce anterior subluxation of the lateral and medial tibial plateau. (**b**) The knee motions during the tests are shown for tibial translation and rotation during knee flexion. The clinical test is shown for the normal knee (*dotted line*) and after ligament sectioning (*solid line*). The ligaments sectioned were the ACL, iliotibial band, and lateral capsule. Position *A* equals the starting position of the test, *B* is the maximum subluxated position, and *C* indicates the reduced position. The pivot shift test involves the examiner applying anterior translation and rotational loading to produce the tibial subluxation. The actual changes in the motion limits are shown later where there are major increases in lateral and medial tibiofemoral compartment translations and only small changes in degrees of internal tibial rotation. *AP* anteroposterior, *div* division (Reprinted from Noyes and Barber-Westin [15])

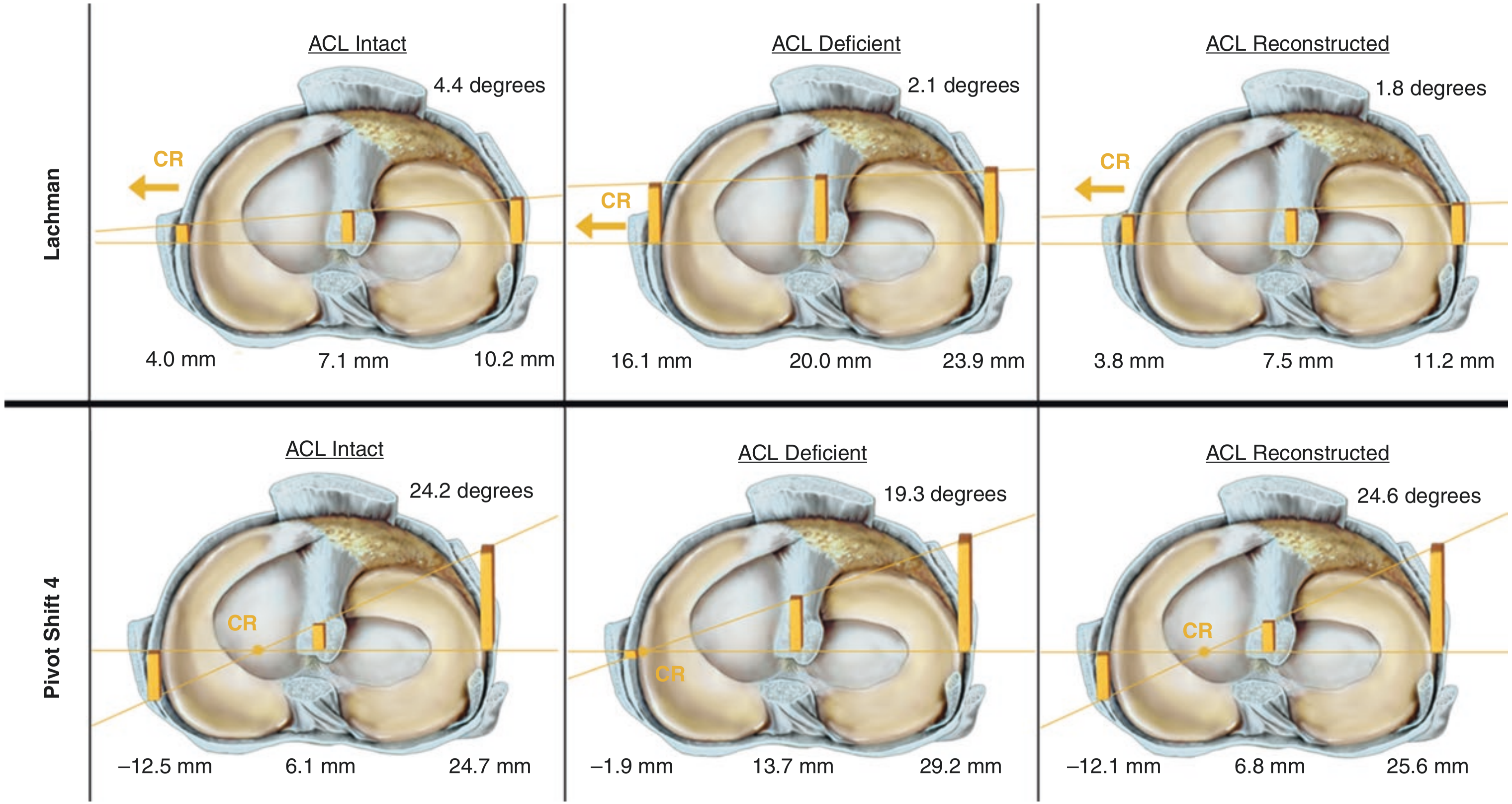


Fig. 19.14 A representative right knee specimen showing compartment translations and tibial rotation under two loading conditions: pivot shift 3 and pivot shift 4. In the pivot shift 3 loading, there is no subluxation of the medial tibiofemoral compartment because the anterior tibial loading was of a small magnitude. In contrast, in the pivot shift 4 loading, a major anterior tibial loading is added along with internal rotation-valgus loading. In addition, the internal tibial torque is reduced from 5 to 1 N-m. There is a medial shift in the center of tibial rotation, with subluxation of the medial, center, and lateral tibiofemoral compartments. Loading conditions for pivot shift 3 were 35 N anterior, 5 N-m internal rotation, and 7 N-m valgus. Loading conditions for pivot shift 4 were 100 N anterior, 1 N-m internal rotation, and 7 N-m valgus. *ACL* anterior cruciate ligament, *CR* center of tibial rotation (Reprinted from Noyes and Barber-Westin [2])

further damage to the knee joint in a manner similar to that of a conservatively treated ACL-deficient knee [16, 17]. Any knee with a positive pivot shift is at increased risk for a recurrent giving-way reinjury, damage to meniscus structures, and future joint arthrosis. The objective rules for RTS in athletes who decline ACL reconstruction apply to obtain correction of parameters such as muscle strength and control; however, the rule is strict that turning, twisting, and deceleration activities are contraindicated due to the risk of further damage to cartilage, meniscus, and ligament structures. Only light recreational activities would be indicated such as biking, swimming, and work-out activities.

19.6.2 Posterior Cruciate Ligament

In patients that undergo PCL reconstruction, the medial posterior tibiofemoral step-off on the posterior drawer test is done at 90° of flexion (Fig. 19.15). It is important to note that the clinical posterior drawer test can be highly subjective because the forces applied may be too variable to allow accurate determination of the status of a PCL reconstruction. If any question arises regarding the reconstructed ligament's integrity, quantification of posterior tibial translation may be performed using stress radiography [7]. Young active patients who demonstrate >10 mm of increased posterior tibial translation and who wish to resume high-risk activities are counseled of the risks for further symptoms and joint damage.

19.6.3 Medial Collateral Ligament

Patients that had damage to or reconstruction of the medial ligament structures (superficial medial collateral ligament, deep medial collateral ligament, and/or posterior oblique ligament [14]), undergo manual valgus stress testing at 0° and 30° of knee flexion (Fig. 19.16). The amount of joint opening is estimated between the initial closed contact position and open position of each tibiofemoral compartment, performed in a constrained manner avoiding internal or external tibial rotation. The result is recorded according to the approximate increase in the tibiofemoral compartment of the affected knee compared with the opposite normal knee. Medial joint opening may also be measured with stress radiographs if required. The majority of patients who sustain damage to the medial ligament structures are treated conservatively; however, there is building evidence that open surgical repair in athletes provides a superior result. A small amount of residual medial compartment opening is not considered a contraindication for RTS. However, a large symptomatic amount of medial opening (>10 mm) is indicative of nonfunctional medial ligament structures and surgery may be discussed. Patients with a combined ACL-MCL

Fig. 19.15 Posterior drawer test performed at 90° of knee flexion, posterior load on proximal tibia, and no tibial rotation. The medial tibiofemoral step-off is palpated (Reprinted from Noyes and Barber-Westin [7])

Fig. 19.16 Valgus stress test, palpating for medial joint opening at 30° and 0° of flexion (Reprinted from Noyes and Barber-Westin [14])

injury must demonstrate restoration of both ligament structures for release to unrestricted athletic activities.

19.6.4 Lateral Collateral Ligament and Posterolateral Structures

In patients who sustained injury to or undergo reconstruction of the LCL and posterolateral structures (popliteus muscle-tendon-ligament unit, including the popliteofibular ligament and posterolateral capsule), manual varus stress testing is performed at 0° and 30° of knee flexion. The surgeon estimates the amount of joint opening (in millimeters) between the initial closed contact position and maximum opened position of the lateral tibiofemoral compartment, performed in a constrained manner avoiding internal or external tibial rotation. The result is recorded according to the increase in the tibiofemoral compartment of the reconstructed knee compared with the opposite normal knee. Lateral tibiofemoral joint opening may be quantified with stress radiographs if required.

The tibiofemoral rotation dial test is performed at 30° and 90° to determine if any increase is present in external tibial rotation with posterior subluxation of the lateral tibial plateau (Fig. 19.17). A word of caution is necessary because it is possible to confuse increased external tibial rotation for a posterolateral insufficiency and not detect that the increase is actually an anterior subluxation of the medial tibial plateau due to medial ligament insufficiency [8]. The examiner palpates both the medial and lateral tibial prominences at the anterior aspect of the joint and visually determines which tibiofemoral compartment is abnormal (anterior subluxation of the medial tibial plateau or posterior subluxation of the lateral tibial plateau). The senior author initially described the dial test and recommended the supine position to visualize the anterior aspect of the joint. Later modification of performing the test in the prone position is not recommended because the examiner cannot determine which tibiofemoral compartment is undergoing a rotational subluxation.

Because injury to the lateral and posterolateral structures is frequently accompanied by ACL or PCL ruptures, the determination of the function of all injured or reconstructed ligaments is crucial in the RTS decision process. In these cases, articular cartilage damage is often present and patients are advised to return to low-impact activities such as bicycling, swimming, low-impact aerobics,

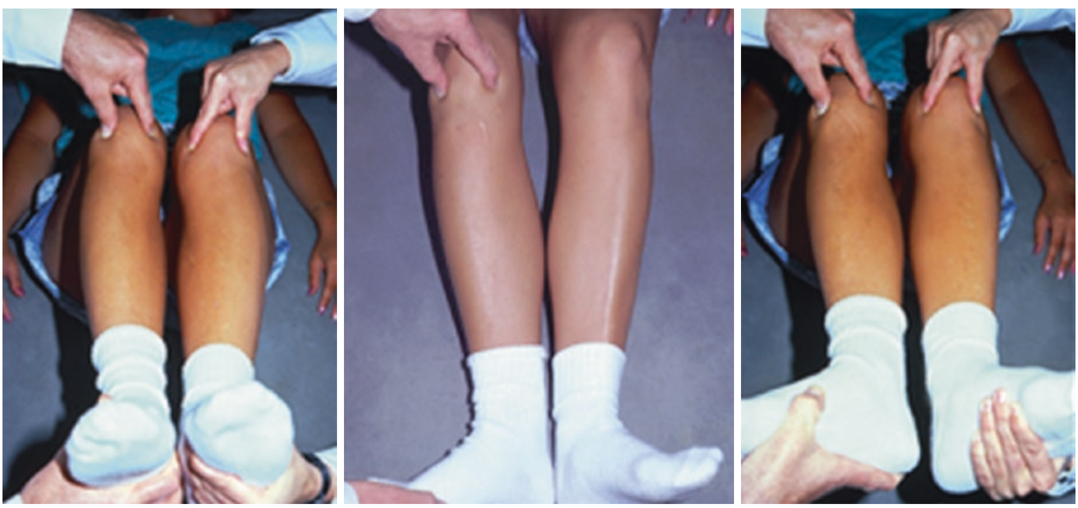


Fig. 19.17 External rotation-internal rotation dial test. (*Left*) Starting position (performed at 30° and 90° of flexion). (*Center*) Maximum at 30° of flexion. (*Right*) Maximum at 90° of flexion (Reprinted from Noyes and Barber-Westin [14])

and low-impact fitness training. Patients with combined ligament injuries must demonstrate restoration of all ligament structures and no or only mild damage to the articular cartilage for release to unrestricted athletic activities.

19.7 Determination of Articular Cartilage Damage

It is well appreciated that up to 20% of athletes with ACL injury will also sustain damage to the articular cartilage as a result of the traumatic anterior subluxation of the medial and lateral tibial plateaus. The pattern of damage to the lateral tibiofemoral compartment is well understood as the posterior tibial plateau impinges against the anterior aspect of the lateral femoral condyle. Bone bruise patterns indicating micro-trabecular fracture of both the tibia and femur occur in up to 70–80% of injuries [18, 19]. More serious micro-trabecular fractures may be associated with chondrocyte death and later articular cartilage thinning and early arthrosis. Potter et al. [20] studied the incidence of lateral tibiofemoral compartment arthrosis after ACL injury and reported that, by 7–11 years post-injury, the risk of cartilage loss was 50 times that of baseline. In addition to the MRI findings, it is important for the entire management team to be aware of the findings at arthroscopy in which a careful examination documents damage to articular cartilage surfaces. Appropriate arthroscopic photographs are required, which become a permanent part of the operative treatment records. The extent of initial cartilage damage greatly influences the recommendation to return to high impact athletic activities. Subsequent MRI imaging with specific cartilage views is available prior to RTS and, as well, at follow-up if necessary to detect early cartilage damage that may contraindicate certain high impact sports. This is also important in knees with associated meniscus damage, such as after a partial meniscectomy in which there may be further joint damage with sports.

A highly controversial subject relates to athletes that sustain serious meniscus injury in which a high grade partial or complete meniscectomy is required. There are many natural history studies that indicate certain athletes will develop tibiofemoral arthrosis [21, 22]. Risk factors include a varus or valgus alignment for medial or lateral meniscus loss (Fig. 19.18), respectively, type of sports (high impact versus low impact), frequency

Fig. 19.18 A 33-year-old woman presented with moderate to severe medial joint pain and giving way with daily activities. She had a prior medial meniscectomy 15 years ago and a failed ACL allograft reconstruction 8 years ago. The examination showed a positive pivot shift and 15 mm of increased anteroposterior tibial displacement on KT-2000 testing. There was no increase in external tibial rotation, lateral joint opening, or posterior tibial translation. Full-length, standing radiographs revealed a weight-bearing line of 20% of the tibial width and narrowing of the medial tibiofemoral compartment (Reprinted from Noyes and Barber-Westin [5])

of athletic participation, body mass index, and intrinsic patient factors that are difficult to judge. It is the authors' opinion that loss of meniscus function places the knee joint at considerable risk for joint arthrosis, which contraindicates high impact athletic sports. These patients require routine repeat examinations including weight-bearing PA views (45° knee flexion) to detect any decrease in joint space. Unfortunately, meniscus transplants are not chondroprotective, even though they may have a significant benefit in decreasing joint pain in meniscectomized knees [23]. The International Meniscus Reconstruction Experts Forum concluded that meniscus transplantation is recommended with caution because of concern for high failure rates, which is especially important in athletes [24]. An individualized RTS approach is warranted, recognizing that the main goal is to avoid future wear-related problems.

19.8 Diagnosis of Complex Regional Pain Syndrome

A rare but potentially severe problem is the onset postoperatively of complex regional pain syndrome (CRPS) [25]. Nomenclature relating to CRPS has varied over the years and has included Sudeck's atrophy, reflex sympathetic dystrophy, post-traumatic dystrophy, and causalgia. The disorder usually follows tissue injury or surgery to a limb (although it may have a spontaneous onset) that may be associated with sensory, vasomotor, sudomotor, motor, and dystrophic changes [26]. The pain is distinct in that it is out of proportion to the inciting event and may be accompanied by discoloration of skin, change in skin temperature, abnormal sweating, edema, and loss of the normal range of motion of the affected limb. The early diagnosis and treatment of this disorder is crucial because early management yields a more favorable outcome [27–30]. If not successfully managed, CRPS patients suffer a major loss of quality of life for several years [31] and will most likely experience psychological consequences of their chronic pain [32, 33]. The term *CRPS-I* indicates diagnostic criteria are present without major nerve damage, while the term *CRPS-II* indicates diagnostic criteria exist along with nerve injury, entrapment, or compression, or the formation of a neuroma (Fig. 19.19). The current diagnostic criteria for CRPS, known as the Budapest Criteria, are shown in Table 19.5 [34, 35].

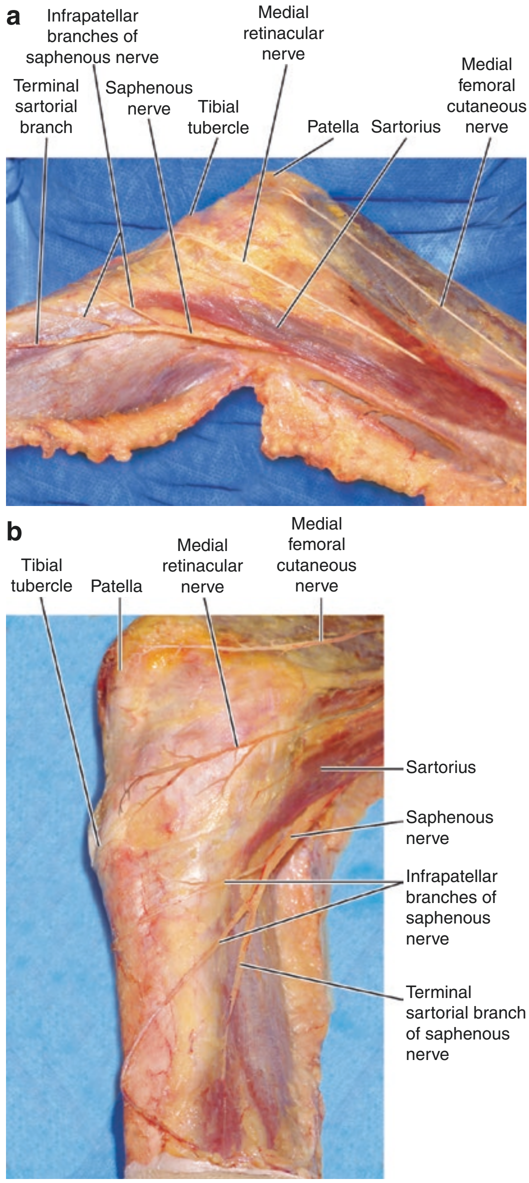


Fig. 19.19 The superficial nerves; (**a**) anteromedial view and (**b**) medial view (Reprinted from Noyes and Barber-Westin [25])

Several theories have been devised to explain the etiology and pathophysiology of CRPS

Table 19.5 Budapest clinical diagnostic criteria for complex regional pain syndrome (CRPS) [34, 35]

General definition of the syndrome:
CRPS describes an array of painful conditions that are characterized by a continuing (spontaneous and/or evoked) regional pain that is seemingly disproportionate in time or degree to the usual course of any known trauma or other lesion. The pain is regional (not in specific nerve territory or dermatome) and usually has a distal predominance of abnormal sensory, motor, sudomotor, vasomotor, and/or trophic findings. The syndrome shows variable progression over time
To make the clinical diagnosis of CRPS, the following criteria must be met:
1. Continuing pain, which is disproportionate to any inciting event
2. Must report at least one symptom in *three of the four* following categories:
Sensory: Reports of hyperesthesia and/or allodynia
Vasomotor: Reports of temperature asymmetry and/or skin color changes and/or skin color asymmetry
Sudomotor/edema: Reports of edema and/or sweating changes and/or sweating asymmetry
Motor/trophic: Reports of decreased range of motion and/or motor dysfunction (weakness, tremor, dystonia) and/or trophic changes (hair, nail, skin)
3. Must display at least one sign at time of evaluation in two or more of the following categories:
Sensory: Evidence of hyperalgesia (to pinprick) and/or allodynia (to light touch and/or deep somatic pressure and/or joint movement)
Vasomotor: Evidence of temperature asymmetry (> 1 ° C) and/or skin color changes and/or asymmetry
Sudomotor/edema: Evidence of edema and/or sweating changes and/or sweating asymmetry
Motor/trophic: Evidence of decreased range of motion and/or motor dysfunction (weakness, tremor, dystonia) and/or trophic changes (hair, nail, skin)
4. There is no other diagnosis that better explains the signs and symptoms

[36–42], most of which discuss CRPS in general and not specifically as it relates to the knee joint [43]. Investigators typically agree that this disorder involves the central, autonomic, and somatic nervous systems, may be influenced by neurogenic inflammation and an immunologic response, creates central sensitization, and may induce cortical reorganization. In the chronic state, tissue ischemia/hypoxia may result from endothelial dysfunction and impaired circulation, and severe psychological distress and neuropsychological impairment may occur.

Common self-reported symptoms include asymmetry in skin color, hyperesthesia (allodynia, hyperpathia), asymmetric edema, and motor changes. Frequent signs observed on physical examination are skin color asymmetry, hyperalgesia, decreased active range of motion, and motor changes. A classic finding is allodynia during the physical exam in which the patient describes the inability to tolerate pressure from bed sheets at night, clothing, and even air currents. The hallmark finding of CRPS is pain disproportionate to the inciting event, including pain more intense than expected, lasting longer than expected, and expanding beyond the dermatomal region of the extremity. The pain may be described as burning and shooting, or as deep, constant, and aching (Fig. 19.20). Pain may worsen with aggressive physical therapy, weather changes (becoming colder), physical activity, and fear or agitation.

In patients with suspected nerve injuries or neuromas, a diagnostic nerve block is indicated [25]. In the knee, this usually involves the infrapatellar branch of the saphenous nerve and may also involve the medial retinacular nerve, the medial cutaneous nerve, and the lateral retinacular nerve. A lumbar sympathetic ganglion block is one tool used for both diagnosing and treating CRPS-I, although its use is controversial. MRI must be done before a lumbar block to detect other possible triggers for pain such as a meniscus tear to avoid the necessity of this test. Treatment options vary and have been descripted in detail elsewhere [44].

References

1. Noyes FR, Grood ES. Scientific basis for examination and classification of knee ligament injuries. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 37–82. https://doi.org/10.1016/b978-0-323-32903-3.00003-2.
2. Noyes FR, Barber-Westin SD. Scientific basis for examination and classification of knee ligament injuries. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 137–82.

Fig. 19.20 (**a**, **b**) Patient indicating site of skin hypersensitivity to touch and a burning sensation on the anteromedial aspect of her knee (Reprinted from Noyes and Barber-Westin [25])

3. Noyes FR, Grood ES. Classification of ligament injuries: why an anterolateral laxity or anteromedial laxity is not a diagnostic entity. Instr Course Lect. 1987;36:185–200.
4. Matheson GO, Shultz R, Bido J, Mitten MJ, Meeuwisse WH, Shrier I. Return-to-play decisions: are they the team physician's responsibility? Clin J Sport Med. 2011;21(1):25–30. https://doi.org/10.1097/JSM.0b013e3182095f92.
5. Noyes FR, Barber-Westin SD. Tibial and femoral osteotomy for Varus and Valgus knee syndromes: diagnosis, osteotomy techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 773–847. https://doi.org/10.1016/b978-0-323-32903-3.00026-3.
6. Noyes FR, Barber-Westin SD. Unicompartmental knee replacement for varus or valgus malalignment. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 882–910.
7. Noyes FR, Barber-Westin SD. Posterior cruciate ligament injuries: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 447–526. https://doi.org/10.1016/b978-0-323-32903-3.00016-0.
8. Noyes FR, Barber-Westin SD. Posterolateral ligament injuries: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 527–77. https://doi.org/10.1016/b978-0-323-32903-3.00017-2.
9. Noyes FR, Barber-Westin SD. Operative options for extensor mechanism malalignment and patellar dislocation. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 970–1013.
10. Noyes FR, Albright J. Reconstruction of the medial patellofemoral ligament with autologous quadriceps tendon. Arthr. 2006;22:904e1–7.
11. McMurray TP. The semilunar cartilages. Br J Surg. 1942;29:407.
12. Mohan BR, Gosal HS. Reliability of clinical diagnosis in meniscal tears. Int Orthop. 2007;31(1):57–60. https://doi.org/10.1007/s00264-006-0131-x.
13. Noyes FR, Barber-Westin SD. Meniscus tears: diagnosis, repair techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 677–718. https://doi.org/10.1016/b978-0-323-32903-3.00023-8.

14. Noyes FR, Barber-Westin SD. Medial and posteromedial ligament injuries: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 608–35. https://doi.org/10.1016/b978-0-323-32903-3.00019-6.
15. Noyes FR, Barber-Westin SD. Anterior cruciate ligament primary reconstruction: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 137–220.
16. Noyes FR, Matthews DS, Mooar PA, Grood ES. The symptomatic anterior cruciate-deficient knee. Part II: the results of rehabilitation, activity modification, and counseling on functional disability. J Bone Joint Surg Am. 1983;65(2):163–74.
17. Noyes FR, Mooar PA, Matthews DS, Butler DL. The symptomatic anterior cruciate-deficient knee. Part I: the long-term functional disability in athletically active individuals. J Bone Joint Surg Am. 1983;65(2):154–62.
18. Chin YC, Wijaya R, Chong le R, Chang HC, Lee YH. Bone bruise patterns in knee injuries: where are they found? Eur J Orthop Surg Traumatol. 2014;24(8):1481–7. https://doi.org/10.1007/s00590-013-1319-6.
19. Papalia R, Torre G, Vasta S, Zampogna B, Pedersen DR, Denaro V, Amendola A. Bone bruises in anterior cruciate ligament injured knee and long-term outcomes. A review of the evidence. Open Access J Sports Med. 2015;6:37–48. https://doi.org/10.2147/OAJSM.S75345.
20. Potter HG, Jain SK, Ma Y, Black BR, Fung S, Lyman S. Cartilage injury after acute, isolated anterior cruciate ligament tear: immediate and longitudinal effect with clinical/MRI follow-up. Am J Sports Med. 2012;40(2):276–85. https://doi.org/10.1177/0363546511423380.
21. Hoser C, Fink C, Brown C, Reichkendler M, Hackl W, Bartlett J. Long-term results of arthroscopic partial lateral meniscectomy in knees without associated damage. J Bone Joint Surg. 2001;83(4):513–6.
22. Magnussen RA, Mansour AA, Carey JL, Spindler KP. Meniscus status at anterior cruciate ligament reconstruction associated with radiographic signs of osteoarthritis at 5- to 10-year follow-up: a systematic review. J Knee Surg. 2009;22(4):347–57.
23. Noyes FR, Barber-Westin SD. Long-term survivorship and function of meniscus transplantation. Am J Sports Med. 2016;44(9):2330–8. https://doi.org/10.1177/0363546516646375.
24. Getgood A, LaPrade RF, Verdonk P, Gersoff W, Cole B, Spalding T, Group I. International meniscus reconstruction experts forum (IMREF) 2015 consensus statement on the practice of meniscal allograft transplantation. Am J Sports Med. 2016; https://doi.org/10.1177/0363546516660064.
25. Noyes FR, Barber-Westin SD. Diagnosis and treatment of complex regional pain syndrome. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 1122–60. https://doi.org/10.1016/b978-0-323-32903-3.00040-8.
26. Turner-Stokes L, Goebel A. Complex regional pain syndrome in adults: concise guidance. Clin Med. 2011;11(6):596–600.
27. Ogilvie-Harris DJ, Roscoe M. Reflex sympathetic dystrophy of the knee. J Bone Joint Surg. 1987;69(5):804–6.
28. Poehling GG, Pollock FE Jr, Koman LA. Reflex sympathetic dystrophy of the knee after sensory nerve injury. Arthroscopy. 1988;4(1):31–5.
29. Poplawski ZJ, Wiley AM, Murray JF. Post-traumatic dystrophy of the extremities. J Bone Joint Surg Am. 1983;65(5):642–55.
30. Jupiter JB, Seiler JG 3rd, Zienowicz R. Sympathetic maintained pain (causalgia) associated with a demonstrable peripheral-nerve lesion. Operative treatment. J Bone Joint Surg Am. 1994;76(9):1376–84.
31. Schwartzman RJ, Erwin KL, Alexander GM. The natural history of complex regional pain syndrome. Clin J Pain. 2009;25(4):273–80. https://doi.org/10.1097/AJP.0b013e31818ecea5.
32. Vaneker M, Wilder-Smith OH, Schrombges P, Oerlemans HM. Impairments as measured by ISS do not greatly change between one and eight years after CRPS 1 diagnosis. Eur J Pain. 2006;10(7):639–44. https://doi.org/10.1016/j.ejpain.2005.10.003.
33. de Mos M, Huygen FJ, van der Hoeven-Borgman M, Dieleman JP, Ch Stricker BH, Sturkenboom MC. Outcome of the complex regional pain syndrome. Clin J Pain. 2009;25(7):590–7. https://doi.org/10.1097/AJP.0b013e3181a11623.
34. Harden RN, Bruehl S, Stanton-Hicks M, Wilson PR. Proposed new diagnostic criteria for complex regional pain syndrome. Pain Med. 2007;8(4):326–31. https://doi.org/10.1111/j.1526-4637.2006.00169.x.
35. Harden RN, Bruehl S, Perez RS, Birklein F, Marinus J, Maihofner C, Lubenow T, Buvanendran A, Mackey S, Graciosa J, Mogilevski M, Ramsden C, Chont M, Vatine JJ. Validation of proposed diagnostic criteria (the "Budapest criteria") for complex regional pain syndrome. Pain. 2010;150(2):268–74. https://doi.org/10.1016/j.pain.2010.04.030.
36. Maihofner C, Seifert F, Markovic K. Complex regional pain syndromes: new pathophysiological concepts and therapies. Eur J Neurol. 2010;17(5):649–60. https://doi.org/10.1111/j.1468-1331.2010.02947.x.
37. Oaklander AL, Fields HL. Is reflex sympathetic dystrophy/complex regional pain syndrome type I a small-fiber neuropathy? Ann Neurol. 2009;65(6):629–38. https://doi.org/10.1002/ana.21692.
38. Goebel A. Complex regional pain syndrome in adults. Rheumatology (Oxford). 2011;50(10):1739–50. https://doi.org/10.1093/rheumatology/ker202.

39. de Mos M, Sturkenboom MC, Huygen FJ. Current understandings on complex regional pain syndrome. Pain Pract. 2009;9(2):86–99. https://doi.org/10.1111/j.1533-2500.2009.00262.x.
40. van Eijs F, Stanton-Hicks M, Van Zundert J, Faber CG, Lubenow TR, Mekhail N, van Kleef M, Huygen F. Evidence-based interventional pain medicine according to clinical diagnoses. 16. Complex regional pain syndrome. Pain Pract. 2011;11(1):70–87. https://doi.org/10.1111/j.1533-2500.2010.00388.x.
41. Beerthuizen A, van 't Spijker A, Huygen FJ, Klein J, de Wit R. Is there an association between psychological factors and the complex regional pain syndrome type 1 (CRPS1) in adults? A systematic review. Pain. 2009;145(1–2):52–9. https://doi.org/10.1016/j.pain.2009.05.003.
42. Schwenkreis P, Maier C, Tegenthoff M. Functional imaging of central nervous system involvement in complex regional pain syndrome. AJNR Am J Neuroradiol. 2009;30(7):1279–84. https://doi.org/10.3174/ajnr.A1630.
43. Dowd GS, Hussein R, Khanduja V, Ordman AJ. Complex regional pain syndrome with special emphasis on the knee. J Bone Joint Surg. 2007;89(3):285–90. https://doi.org/10.1302/0301-620X.89B3.18360.
44. Noyes FR, Barber-Westin SD. Prevention and treatment of knee Arthrofibrosis. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 1059–102. https://doi.org/10.1016/b978-0-323-32903-3.00038-x.

20 Neuromuscular Function, Agility, and Aerobic Testing

Sue Barber-Westin and Frank R. Noyes

20.1 Introduction

Common body mechanics and injury circumstances have been noted in both men and women during anterior cruciate ligament (ACL) ruptures. Video footage obtained during noncontact ACL injuries demonstrates reduced knee flexion angles, increased hip flexion angles, valgus collapse at the knee, reduced ankle plantar flexion angles (flat-footed position), increased hip internal rotation, and increased internal or external tibial rotation [1–3]. Therefore, before athletes are released to return to sport (RTS), tests are recommended that may detect these abnormal mechanics during activities such as landing from a jump, cutting, or side-stepping. Although the majority of research conducted over the past two decades on neuromuscular indices in young athletes has used expensive force plate, multi-camera motion analysis systems, there are cost-effective test methods available. The drop-jump test is one of the most commonly used assessment methods of neuromuscular function landing from a jump. A side-cut is another practical test that may be performed in the clinic setting. Other jumps involving single-leg balance, power, and neuromuscular control (single hop for distance, crossover hop, triple hop, timed hop, single-leg squat) are detailed in Chap. 21.

Agility is a vital component of athletes; a summary of an analysis of change of direction movement that typically occurs in various sports is shown in Table 20.1. The ability to change direction in an efficient and biomechanically safe manner is vital after ACL reconstruction to reduce the risk of reinjury. Agility is acknowledged to be an

Table 20.1 Frequency of agility, or change of direction maneuvers, in various sports[a]

Sport	
Soccer	Players change direction every 2–4 s Players make 1200–1400 changes of direction during a game
Basketball	Players change direction every 2 s Lateral movement equals 22% of total distance covered (as much as 1684 m)
Tennis (competitive)	Lateral movement accounts for 70% of all movement An average of four changes of direction occur per point As many as 1000 changes of direction occur per match
Squash	An average of 580 steps occur per game and 2866 steps occur per match. Most movements are not done in a straight line
Field hockey	Change of direction occurs every 5.5 s
Rugby	Lateral or backward movement occurs a mean of 59 times per match

s second
[a]From Stewart et al. [4]

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_20

independent motor skill and should be tested separately from strength and power. There are several field-based agility tests that appear to be correlated, reliable, and valid in assessing general athletic ability to change direction [4, 5]. Combined with an appropriate analysis of technique, these tests offer the clinician the ability to assess the patient's technique and confidence in accelerating, decelerating, and changing body direction. Common field tests include the *T*-test [6, 7], the Illinois agility test [8], the 505 test [9], and the pro-agility test [10, 11]. The examiner may consider these options and choose the test that is best suited to the sport the athlete wishes to resume [5, 12–17]. Examples of sports-specific agility tests are provided in Chaps. 17 and 18.

Aerobic fitness is a critical component for athletic performance and injury prevention [18]. Maximal oxygen uptake (VO_2max) is most accurately measured using laboratory tests; however, they are expensive, time-consuming, and require trained personnel. These procedures typically measure VO_2max using indirect pulmonary gas exchange during a maximal treadmill run or stationary bicycle test. In order to provide coaches, athletes, and trainers with a simpler and more feasible alternative, field tests have been developed that provide an estimate of VO_2max. Two of the most common assessments discussed in this chapter are the 20-m multistage fitness test (MSFT) [19] and the Yo-Yo Intermittent Recovery test [20]. While the MSFT assesses continuous aerobic performance, many sports involve intermittent exercise, such as basketball, soccer, rugby, and tennis. Athletes must be able to perform repeated bouts of intense activity, followed by short periods of rest. For these individuals, tests of continuous aerobic endurance may not be relevant as they do not mimic the demands of their sport [21–23]. The Yo-Yo Intermittent Recovery Test was developed to measure an athlete's ability to repeatedly perform intense exercise [20].

Before testing at our center, the athlete completes the dynamic warm-up component of Sportsmetrics training (see Chap. 14). Each test is thoroughly explained and the athlete is allowed several practice trials so that they are familiar with the procedures. Education of the athlete regarding the importance of testing and the need for the maximal effort is crucial to obtain valid results. If several tests are going to be conducted, the least fatiguing tests are conducted first, including highly skilled tasks such as agility or hopping/jumping, and endurance or fatiguing tests are done last. The National Strength and Conditioning Association suggests the following order: non-fatiguing (resting heart rate, body composition, flexibility, and jump tests), agility, power and strength, sprints, local muscular endurance, anaerobic capacity, and aerobic capacity tests [10]. Informed consent is obtained from the athlete if they are ≥18 years of age, or from a parent or legal guardian if they are <18 years old. Ideally, the pre-train and post-train test conditions should be as identical as possible in regard to the day of the week, time of day, environmental conditions if testing is conducted outdoors, and test administrators. Appropriate rest periods are mandatory between tests to allow recovery of normal heart rate, hydration, and preparation for the next task. For instance, power tests that last for a few s (vertical jump height, single-leg hop test) and strength and speed tests lasting around 4 s require 3–5 min between trials [24]. Longer lasting tests may require 8 min between repetitions or test trials.

20.2 Cost-Effective Neuromuscular Function Tests

20.2.1 Video Drop-Jump Screening Test

A drop-jump video screening test may be used to measure overall lower limb alignment in the coronal plane [25–27]. Performed with a single camera in any setting, this procedure clearly demonstrates lower extremity alignment on landing and is useful to conduct after athletes complete neuromuscular training in order to determine if poor landing mechanics improved (Fig. 20.1).

A camcorder equipped with a memory stick is placed on a stand 102.24 cm in height. The stand is positioned approximately 365.76 cm in front of

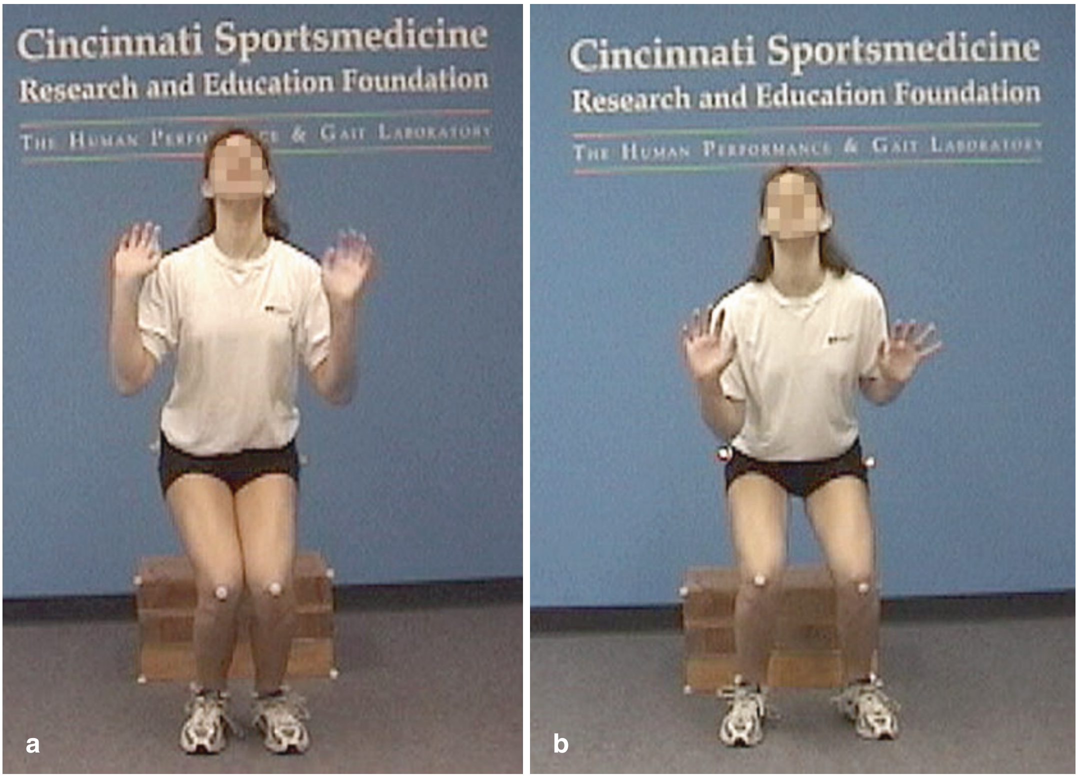


Fig. 20.1 The drop-jump land sequences from a 16-year-old female athlete (**a**) before and (**b**) after neuromuscular training. This volleyball player improved in both the absolute cm of knee separation distance (from 15 to 29 cm) and normalized knee separation distance (from 72 to 94%). (From Barber-Westin and Noyes [28])

a box 30.48 cm in height and 38.1 cm in width. Velcro circles (2.54 cm) are placed on each of the four corners of the box that faces the camera. The athlete is dressed in fitted, dark shorts and low cut gym shoes. Reflective markers are placed at the greater trochanter and lateral malleolus of both legs and velcro circles are placed on the center of each patella. The jump-land sequence is demonstrated and practice trials are allowed to ensure the athlete understands the test. No verbal instructions regarding how to land or jump are provided. The athlete is only instructed to land straight in front of the box to be in the correct angle for the camera to record properly. The athlete performs a jump-land sequence by first jumping off the box, landing, and immediately performing a maximum vertical jump. This sequence is repeated three times.

After completion of the test, all three trials are viewed and the one that best represents the athletes' jumping ability is selected for measurement. Advancing the video frame-by-frame, the following images are captured as still photographs: (1) pre-land, the frame in which the athletes' toes just touch the ground after the jump off of the box; (2) land, the frame in which the athlete is at the deepest point; and (3) take-off, the frame that demonstrates the initial forward and upward movement of the arms and the body as the athlete prepares to go into the maximum vertical jump.

The captured images are imported into a hard drive of a computer and digitized on the screen using commercially available software (sportsmetrics.org). A calibration procedure is done by placing the cursor and clicking in the center of each Velcro marker on each of the four corners of the drop jump box. The anatomic reference points represented by the reflective markers are selected by clicking in a designated sequence the cursor for each image.

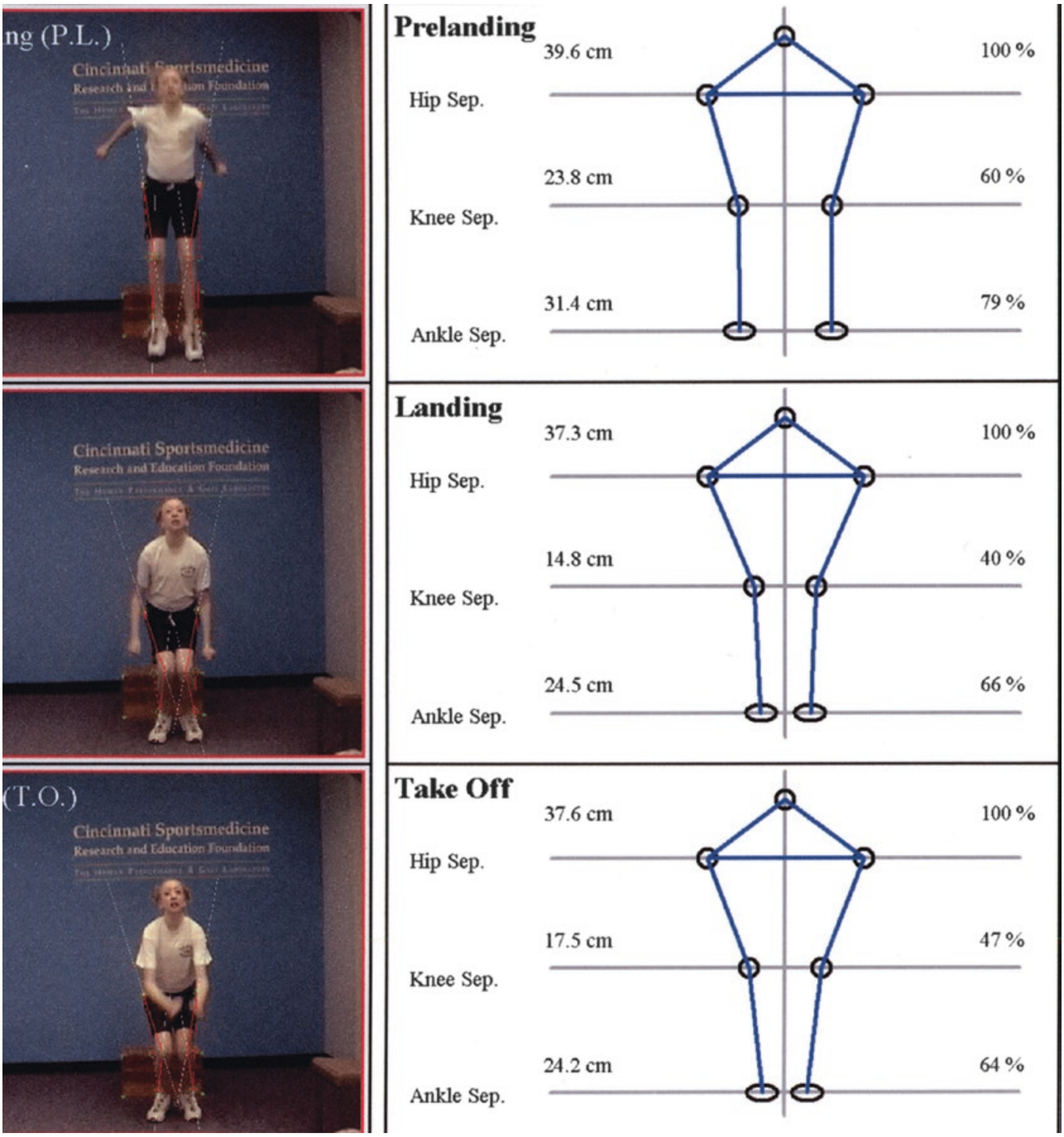


Fig. 20.2 Photographs of the three phases of the drop-jump test. The cm of distance between the hips, knees, and ankles is calculated along with normalized knee and ankle separation distances (according to the hip separation distance). Shown is the test result of a 14-year-old female (From Noyes et al. [25])

The absolute cm of separation distance between the right and left hip and normalized separation distances for the knees and ankles, standardized according to the hip separation distance, are produced using the software. Normalized knee separation distance is calculated as knee separation distance/hip separation distance ×100 and normalized ankle separation distance is calculated as ankle separation distance/hip separation distance ×100 (Fig. 20.2). We empirically believe that <60% knee separation distance represents a distinctly abnormal lower limb valgus alignment position.

The reliability of the drop-jump video test was determined previously [25]. Test-retest trials produced high intraclass correlation coefficients (ICC) for the hip separation distance (pre-land, 0.96; land, 0.94; take-off, 0.94). For the within-test trial, the ICCs for the hip, knee, and ankle separation distance were all ≥0.90, demonstrating excellent reliability of the videographic test and software capturing procedures. A study from an independent center reported high inter-rater reliability between athletic trainers, physical therapists, surgeons, and coaches in determining knee separation distance (K coefficient = 0.92) [26].

If desired, a second camera may be implemented to assess knee and hip flexion angles in the sagittal plane [29]. A third option is to use a camera in the coronal plane to measure or classify lower limb alignment during motions such as cutting. Athletes may be categorized as valgus, varus, or neutral by observing the angle between the shank and thigh in the frame that represents the initiation of the cutting maneuver [30].

It is important to note that the video drop-jump test only provides a general indicator of an athletes' lower limb axial alignment in the coronal plane in a straightforward drop-jump and vertical take-off task and cannot be used as a specific risk indicator for noncontact ACL injuries. This test is performed during one maneuver that only depicts hip, knee, and ankle positions in a single plane, whereas noncontact ACL injuries frequently occur in side-to-side, cutting, or multiple complex motions. More sophisticated and expensive multi-camera systems are required to measure these types of motions in multiple planes [31]. However, this test provides a general assessment of lower limb position and depicts those athletes who have poor control on landing and acceleration into a vertical jump. It is reliable, practical, and feasible for individuals who do not have funds or access to multiple cameras, force plates, and research personnel required to perform extensive data collection and reduction with more complex systems. Sample results for a variety of athletes are shown in Table 20.2 [25, 32–38].

Table 20.2 Sample results of the drop-jump screening test

Study	Cohort details (age)	Normalized knee separation distance on landing (%)
Noyes et al. [25]	*Athletes, male and female, 11–19 years*	
	Female trained	68
	Female control	51
	Male control	51
Noyes et al. [32]	*Basketball, female, high school, 14–17 years*	
	Pre-train	45 ± 17
	Post-train	74 ± 19
Noyes et al. [33]	*Soccer, female, high school, 14–17 years*	
	Pre-train	36 ± 7
	Post-train	54 ± 14
Rodriguez et al. [34]	*Soccer, female, elite, 18.6 ± 2.7 years*	
	Pre-train	41 ± 8
	Post-train	45 ± 12
Noyes et al. [35]	*Volleyball, female, high school, 14–17 years*	
	Pre-train	56 ± 19
	Post-train	63 ± 13
Noyes et al. [36]	*Athletes, female, high school and club, 13–18 years*	
	Pre-train	47 ± 19
	Post-train	65 ± 18
Barendrecht et al. [37]	*Handball, male and female, 13–19 years*	
	Neuromuscular train: pre/post train	54/60
	Regular train: pre/post train	50/52
Chimera and Kremer [38]	*Rowers, female, high school, 15.6 ± 1.2 years*	
	Pre-train	58 ± 12
	Post-train	69 ± 7

20.2.2 Video Plant and Cut Test

Although this test has been used extensively in laboratories with multiple cameras, force plates, and equipment required to capture three-dimensional kinematics and kinetics, it may be used to subjectively rate trunk and lower extremity mechanics during a plant and 45° cut maneuver. This test is performed as described by Pollard et al. [39] where the patient runs 5 m to a spot designated on the floor with tape, plants on the involved leg, and then performs a 45° cut. If the right leg was reconstructed, the cut should be to the left. Cones may be set up to direct the patient to perform the angle of 45°. The examiner should watch for excessive trunk lean over the stance leg, poor hip and/or knee flexion, and valgus collapse at the knee [40, 41].

Pollard et al. [39] reported gender differences during this test in collegiate soccer players. During the early deceleration phase, female athletes demonstrated differences in hip kinematics and kinetics compared with male athletes in greater hip internal rotation (7.7° and −1.0°, respectively, $P = 0.01$), less hip flexion (49° and 54°, respectively, $P = 0.05$), greater hip adductor moments (−1.69 Nm/kg and −0.87 Nm/kg, respectively, $P = 0.04$), and decreased hip extensor moments (5.36 Nm/kg and 6.67 Nm/kg, respectively, $P = 0.04$). McLean et al. [42] reported that female collegiate basketball players had significantly larger knee valgus moments at peak stance phase compared with their male counterparts (0.63 ± 0.20 Nm kg^{-1} m^{-1} and 0.42 ± 0.11, Nm kg^{-1} m^{-1}, respectively, $P < 0.05$), which were associated with larger initial hip flexion and internal rotation and larger knee valgus angles. Malinzak et al. [43] reported that collegiate female recreational athletes demonstrated lower knee flexion angles (mean difference, 8°) and greater valgus angles (mean difference, 11°) during stance phase than male athletes. Sigward and Powers [44] found that, when compared to males athletes, females had smaller peak knee flexor moments (1.4 ± 0.8 Nm/kg and 2.1 ± 0.8 Nm/kg, respectively, $P = 0.05$), and greater knee adductor moments (0.43 ± 0.5 Nm/kg and 0.01 ± 0.3 Nm/kg, respectively, $P < 0.01$) during the early deceleration phase of this task.

20.3 Agility Tests

20.3.1 *T*-test

Since its initial description in the literature in 1990 [45], the *T*-test has become one of the most widely used measures of agility [4, 7, 12, 14, 17, 33, 46–59]. The athlete sprints from a standing point in a straight line to a cone placed 9-m away (Fig. 20.3). Then, the athlete side-shuffles to their left without crossing their feet to another cone placed 4.5-m away. After touching this cone, they side-shuffle to their right to a third cone placed 9-m away, side-shuffle back to the middle cone, and then run backwards to the starting position. Two tests are completed, with the best time recorded. The time to complete this test is recorded with a digital stopwatch in one-hundredths of a second. This test has excellent reliability, with ICCs ≥0.90 [4, 6, 7, 57, 60, 61]. The results may be compared with published data according to sports and gender (Table 20.3).

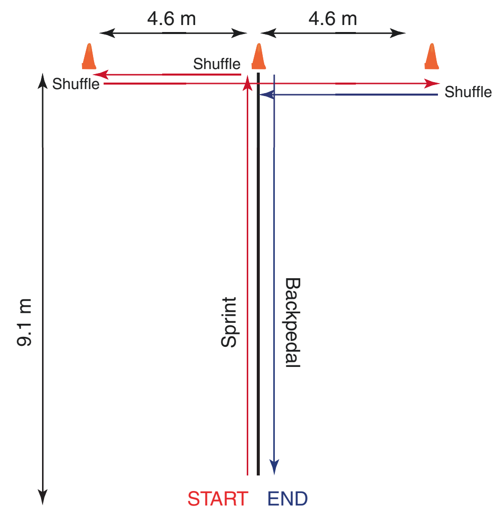


Fig. 20.3 *T*-test. The test requires the athlete to follow the directions shown with the arrows from start to finish

20.3.2 Pro-Agility Test

Also known as the 5-10-5 test, the pro-agility test is another common field test (Fig. 20.4) [4, 5, 11, 50, 53, 63–72]. The athlete begins on a marked line, sprints 4.5 m to a second line, and touches the line with their hand. The athlete then turns 180° and sprints to a third line that is 9.1 m away. They touch that line, turn 180° again, and return to the starting line (4.5 m) away. The athlete is instructed to sprint through the starting point. Two tests are completed, with the best time recorded. The time to complete this test is recorded with a digital stopwatch in one-hundredths of a second. This test has excellent reliability, with ICC >0.90 [4, 70]. The results may be compared with published data according to sports and gender (Table 20.4).

Table 20.3 Sample results of the *T*-test

Study	Cohort details (age)	*T*-test (s)
Ben Abdelkrim et al. [47]	*Basketball, male, elite, 18.2 ± 0.5 years*	
	No train, profile only	11.56 ± 0.46
Asadi et al. [46]	*Basketball, male, elite, 18.5 ± 0.8 years*	
	Train	12.20 ± 0.32
	Control	12.90 ± 0.54
Spiteri et al. [58]	*Basketball, female, professional, 24.2 ± 2.5 years*	
	No train, profile only	11.75 ± 1.15
Delextrat et al. [12]	*Basketball, female, elite, age NA*	
	No train, profile only	10.45 ± 0.51
Delextrat et al. [48]	*Basketball, male, age NA*	
	Elite level	9.21 ± 0.24
	Average level	9.78 ± 0.59
Hoffman et al. [50]	*Lacrosse, female, elite, 19.2 ± 1.0 years*	
	Starters	10.5 ± 0.6
	Nonstarters	10.5 ± 0.2
McFarland et al. [53]	*Soccer, collegiate, 18–23 years*	
	Females	11.92 ± 0.56
	Males	10.22 ± 0.41
Kutlu et al. [62]	*Soccer, female, collegiate, 20.8 ± 1.9 years*	
	Trial #1	12.17 ± 0.56
	Trial #2	12.21 ± 0.53
Noyes et al. [33]	*Soccer, female, high school, 15 ± 1 years*	
	Pre-train	12.05 ± 0.87
	Post-train	11.31 ± 0.69
Sporis et al. [17]	*Soccer, male, elite, 19.1 ± 0.6 years*	
	No train, profile only	8.12 ± 0.27
Negra et al. [56]	*Athletes, male, 12 ± 1 years*	
	Soccer	11.90 ± 0.80
	Handball	12.89 ± 1.34
Sekulic et al. [57]	*Tennis, male and female, competitive, 18 ± 2 years*	
	Trial #1	12.29 ± 1.01
	Trial #2	12.01 ± 0.99
	Trial #3	11.94 ± 1.10
Gabbett et al. [49]	*Volleyball, 16.5 ± 0.1 years*	
	National, male	9.90 ± 0.17
	National, female	10.33 ± 0.13
	State, male	9.76 ± 0.15
	State, female	10.55 ± 0.14
	Novice, male	10.47 ± 0.18
	Novice, female	11.23 ± 0.16
Jarvis et al. [14]	*Rugby, male, sub-elite, 23.0 ± 5.4 years*	
	Forwards	12.5 ± 1.3
	Backs	10.9 ± 0.5
	All	11.7 ± 1.3
Khodaei et al. [51]	*Athletes, male, 20 ± 1 years*	
	Assisted plyometric trained	8.25 ± 0.48
	Resisted plyometric trained	8.27 ± 0.69
	Common plyometric trained	8.64 ± 0.66
Stewart et al. [4]	*Healthy physical education students, 16.7 ± 0.6 years*	
	Male	10.31 ± 0.46
	Female	11.70 ± 0.67
Miller et al. [54]	*Athletes, gender NA, 22.3 ± 3.1 years*	
	Pre-train	12.8 ± 1.0
	Post-train	12.1 ± 1.1
Munro et al. [7]	*Recreationally active, male and female, collegiate, 22 ± 3 years*	
	Male	11.28 ± 0.75
	Female	13.36 ± 0.92

NA not available

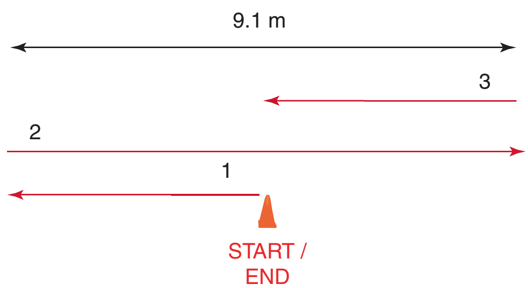


Fig. 20.4 The pro-agility test consists of three forward sprints as shown. Course shown is an American football field

Table 20.4 Sample results of the pro-agility test

Study	Cohort details (age)	Pro-agility (s)
Arede et al. [63]	*Basketball, male, 14.2 ± 0.4 years*	
	Pre-train	5.54 ± 0.20
	Post-train	5.50 ± 0.17
Hoffman et al. [50]	*Lacrosse, female, elite, 19.2 ± 1.0 years*	
	Starters	4.92 ± 0.22
	Nonstarters	4.94 ± 0.13

(continued)

Table 20.4 (continued)

Study	Cohort details (age)	Pro-agility (s)
Lockie et al. [68]	*Soccer, female, collegiate, 20.1 ± 1.2 years*	
	No train, profile	5.09 ± 0.23
McFarland et al. [53]	*Soccer, collegiate, 18–23 years*	
	Females	5.36 ± 0.18
	Males	4.64 ± 0.14
Vescovi et al. [71]	*Soccer, female, high level*	
	Age 12–13 years	5.17 ± 0.33
	Age 14–17 years	4.92 ± 0.24
	Age 18–21 years	4.87 ± 0.21
Vescovi et al. [5]	*Soccer, female*	
	High school, age 15.1 ± 1.6 years	4.91 ± 0.22
	Collegiate, age 19.9 ± 0.9 years	4.88 ± 0.20
	Lacrosse, female	
	Collegiate, age 19.9 ± 0.9 years	4.99 ± 0.24
Magal et al. [69]	*Soccer, male, elite, 20.0 ± 0.9 years*	
	Preseason	4.96 ± 0.19
	Postseason	4.80 ± 0.33
Bishop et al. [64]	*Rugby, male elite, U17*	
	No train, profile only	4.67 ± 0.16
McKay et al. [73]	*American football, male, high school, defensive backs*[a]	
	Freshman	4.61 ± 0.24
	Sophomore	4.52 ± 0.22
	Junior	4.46 ± 0.20
Collins et al. [65]	*American football, male, high school, 15.9 ± 0.9 years*	
	No train, profile only	5.03 ± 0.21
Mann et al. [70]	*American football, male, collegiate, 20.5 ± 1.2 years*	
	Trial #1	4.53 ± 0.35
	Trial #2	4.54 ± 0.31
Yuasa et al. [72]	*American football, male, collegiate, 19.9 ± 0.9 years*	
	No train, profile only	4.43 ± 0.13
Fitzgerald et al. [66]	*American football, male, professional*	
	1999–2000 NFL Combines	4.37 ± 0.26
	2015–2016 NFL Combines	4.39 ± 0.26
Stewart et al. [4]	*Healthy physical education students, 16.7 ± 0.6 years*	
	Male	4.88 ± 0.26
	Female	5.35 ± 0.28
Jones et al. [11]	*Healthy athletic preadolescents, 11.7 ± 0.5 years*	
	Male	5.99 ± 0.47
	Female	5.84 ± 0.45
Jones et al. [67]	*Collegiate female athletes (soccer, field hockey, softball), age NA*	
	Pre-train	5.39 ± 0.24
	Post-train	5.37 ± 0.25

NFL National Football League, *NA* not available
[a]Data also available for other positions, see article

20.3.3 Illinois Agility Test

The Illinois agility test has been widely used to measure agility in a variety of athletes [4, 14, 46, 51, 54, 56, 57, 62, 74–84]. This timed test involves straight sprinting, multiple directional changes around cones, and 180° turns (Fig. 20.5). Results may be compared with published data shown in Table 20.5. The reliability of this test is excellent, with ICCs >0.90 [56, 61, 62, 78, 81, 85].

20.3.4 505 Test

This agility test requires an electronic timing system (Fig. 20.6); we include it in this chapter because it is another frequently used assessment method of the ability of athletes to change direction. The athlete runs straight ahead for 10 m and, upon passing the timing gate, sprints 5 more m, makes a 180° turn, and sprints 5 m back through the timing gate. Results may be compared with published data shown in Table 20.6 [58, 86–99, 101, 102]. The reliability of this test is adequate, with ICCs ranging from 0.68 [100] to 0.94 [96].

20.4 Aerobic Tests

20.4.1 Estimated Maximal Oxygen Uptake: Multistage Fitness Test

Equipment required for the MSFT are a commercially available audio compact disk (CD) and a CD player. Two cones are used to mark the course (Fig. 20.7). The athlete begins with their toes behind the designated starting cone. The second cone is located 20 m away. The athlete is instructed that, on the "go" command, they are to begin running back and forth between the two cones in time to recorded beeps on the CD. The athlete performs shuttle runs back and forth along the 20-m course, keeping in time with the series of signals (beeps) on the CD by touching the appropriate end cone in time with each audio signal. The frequency of the audible signals (and

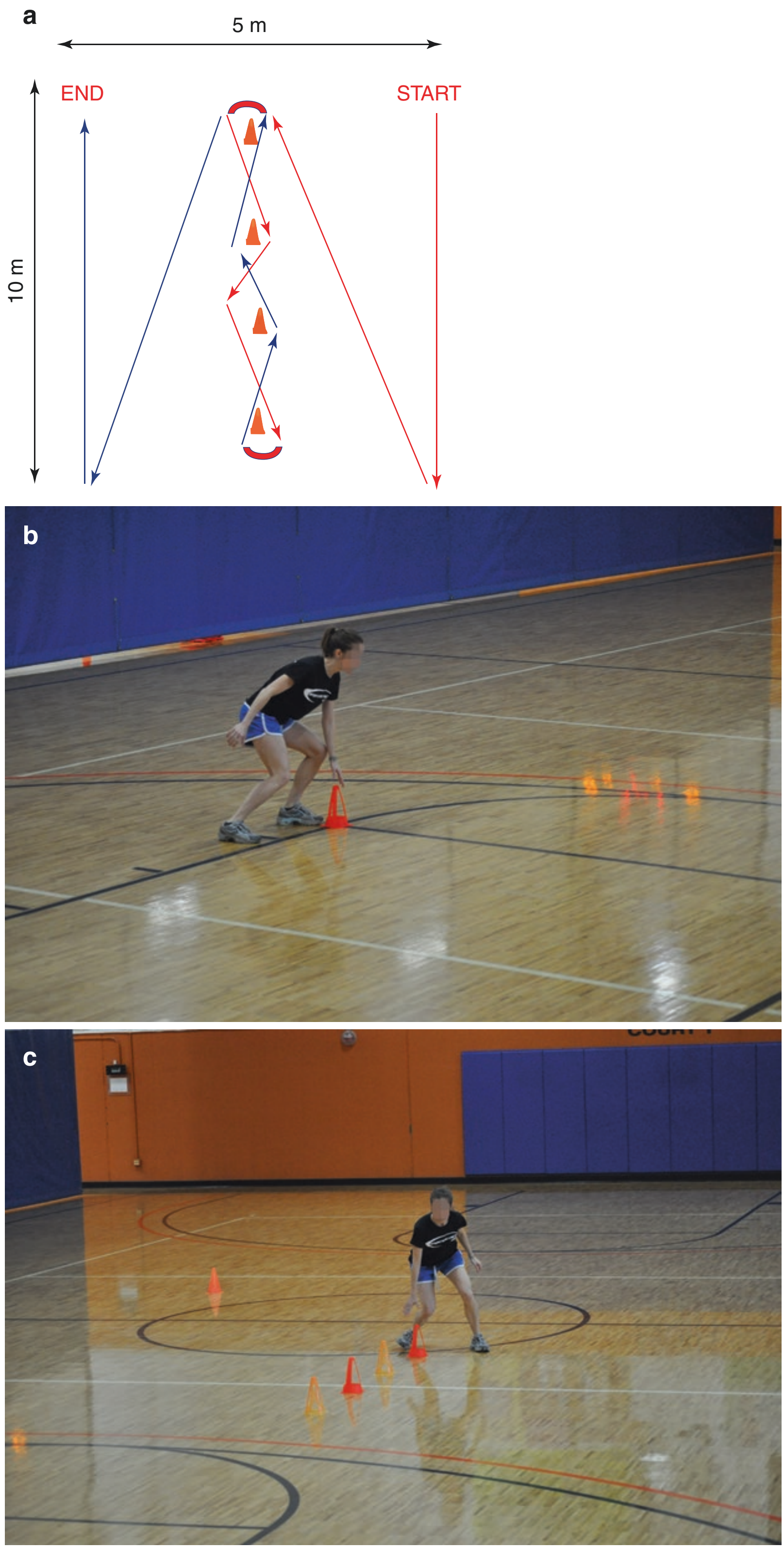


Fig. 20.5 The (**a**) Illinois test course with the first section marked by the red lines and the second section marked by the blue lines and (**b**, **c**) direction. (**b** and **c** from Barber-Westin and Noyes [28])

Table 20.5 Sample results of the Illinois agility test

Study	Cohort details (age)	Illinois (s)[a]
Amiri-Khorasani et al. [74]	*Soccer, male, professional, 22.5 ± 2.5 years*	
	No stretch warm-up	14.18 ± 0.66
	Static stretch warm-up	14.90 ± 0.38
	Dynamic stretch warm-up	13.95 ± 0.32
	Combined stretch warm-up	14.50 ± 0.35
Daneshjoo et al. [75]	*Soccer, male, professional, 18.9 ± 1.4 years*	
	Train 11+	14.4 ± 0.3
	Train HarmoKnee	15.5 ± 0.2
	Control	16.9 ± 1.2
Kutlu et al. [62]	*Soccer, female, collegiate, 20.8 ± 1.9 years*	
	Trial #1	19.07 ± 0.70
	Trial #2	19.12 ± 0.74
Vazini Taher et al. [84]	*Soccer, gender NA, collegiate, age 23 ± 4 years*	
	Static warm-up	16.53 ± 1.64
	Dynamic warm-up	15.14 ± 0.89
	FIFA 11+ warm-up	16.56 ± 0.79
Howard and Stavrianeas [79]	*Soccer, gender NA, high school*	
	Pre-train	16.26 ± 1.02
	Post-train	16.29 ± 0.92
Makhlouf et al. [81]	*Soccer, male, 10–12 years*	
	Balance and plyometric trained	18.16 ± 0.8
	Agility and plyometric trained	18.00 ± 0.6
	Control	18.38 ± 0.6
Negra et al. [82]	*Soccer, male, 12.2 ± 0.5*	
	Pre-train	18.25 ± 0.53
	Post-train	16.81 ± 0.22
Zarei et al. [85]	*Soccer, male, elite, 14–16 years*	
	Pre-train	19.1 ± 0.9
	Post-train	18.3 ± 0.8
Asadi et al. [46]	*Basketball, male, elite, 18.5 ± 0.8 years*	
	Control group	18.97 ± 0.72
	Trained group	17.81 ± 0.71
Fiorilli et al. [76]	*Basketball, gender NA, high-level, 15.2 ± 0.9 years (9.3 × 7.2 m course)*	
	Defenders	11.40 ± 1.43
	Midfielders	10.97 ± 0.90
	Forwards	11.61 ± 1.61
Gabbett et al. [77]	*Rugby, male, sub-elite level, forwards/backs*	
	First grade, senior league	17.2/17.4
	Second grade, senior league	18.1/17.7
	Under 19	18.3/17.9
	Under 16	19.4/19.1
	Under 15	19.5/19.5
	Under 14	21.1/20.3
	Under 13	22.0/21.5
Jarvis et al. [14]	*Rugby, male, sub-elite, 23.0 ± 5.4 years*	
	Forwards	17.9 ± 0.8
	Backs	16.8 ± 0.6
	All	17.4 ± 0.9
Keogh et al. [80]	*Field hockey, female, regional and club levels, 20 ± 1 years*	
	Regional	16.68 ± 0.16
	Local club	18.03 ± 0.19
Sekulic et al. [57]	*Tennis, male and female, competitive, 18 ± 2 years*	
	Trial #1	19.55 ± 1.30
	Trial #2	19.80 ± 1.56
	Trial #3	19.46 ± 1.43
Roopchand-Martin and Lue-Chin [83]	*Netball, female, elite, 18.6 ± 2.4 years*	
	Pre-train	18.03 ± 1.12
	Post-train	17.58 ±.58
Hachana et al. [78]	*Team sport athletes, male, 20.8 ± 1.3 years (9.2 × 7.2 m course)*	
	Trial #1	16.30 ± 0.77
	Trial #2	16.23 ± 0.83
Khodaei et al. [51]	*Athletes, male, 20 ± 1 years*	
	Assisted plyometric trained	17.35 ± 0.41
	Resisted plyometric trained	17.08 ± 0.44
	Common plyometric trained	17.67 ± 0.52
Negra et al. [56]	*Athletes, male, 12 ± 1 years*	
	Soccer players	18.01 ± 0.87
	Handball players	18.44 ± 0.88
Miller et al. [54]	*Athletes, gender NA, 22.3 ± 3.1 years*	
	Pre-train	17.1 ± 1.7
	Post-train	16.6 ± 1.6
Stewart et al. [4]	*Healthy physical education students, 16.7 ± 0.6 years*	
	Male	15.74 ± 0.84
	Female	17.33 ± 0.73

NA not available
[a]All used 10 × 5 m course unless indicated

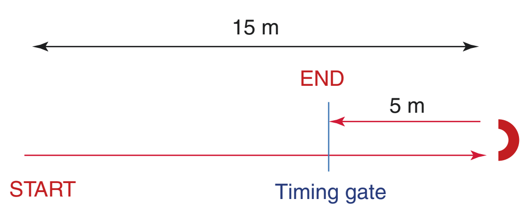


Fig. 20.6 The 505 test consists of two forward sprints as shown

Table 20.6 Sample results of the 505 agility test

Study	Cohort details (age)	505 (s)[a]
Andersen et al. [86]	*Soccer, female, collegiate Division II, 19.7 ± 1.2 years*	
	Right leg turn	2.64 ± 0.12
	Left leg turn	2.68 ± 0.12
Lockie et al. [87]	*Soccer, female, collegiate, 19.9 ± 1.3 years*	
	Division I	2.40 ± 0.10
	Division II	2.60 ± 0.11
Emmonds et al. [88]	*Soccer, female, elite, 25.4 + 7.0 years*	
	Start of season	2.38 ± 0.07
Beato et al. [89]	*Soccer, male, elite, 17 ± 0.8 years*	
	Change direction and plyometric trained	4.73 ± 0.12
	Change of direction trained	4.79 ± 0.12
Tomas et al. [90]	*Soccer, gender NA, elite, 15.6 ± 0.4 years*	
	Profile	2.42 ± 0.09
Dragijsky et al. [91]	*Soccer, gender NA, 11.7 ± 0.5 years*	
	Start of season, dominant leg turn	2.81 ± 0.09
	End of season, dominant leg turn	2.72 ± 0.06
	Start of season, nondominant leg turn	2.83 ± 0.09
	End of season, nondominant leg turn	2.71 ± 0.09
Darrall-Jones et al. [92]	*Rugby, male, elite*	
	Under 16, age 15.5 ± 0.3, left/right	2.51 ± 0.17/2.54 ± 0.14
	Under 18, age 16.9 ± 0.5, left/right	2.57 ± 0.12/2.52 ± 0.13
	Under 21, age 19.0 ± 1.1, left/right	2.41 ± 0.10/2.37 ± 0.15
Jones et al. [93]	*Rugby, female, elite*	
	Forwards, age 26.3 ± 6.4 years, left/right	2.74 ± 0.21/2.70 ± 0.15
	Backs, age 23.5 ± 4.1 years, left/right	2.58 ± 0.14/2.59 ± 0.11
Gabbett et al. [94]	*Rugby, female, elite, 18.9 ± 5.7 years*	
	Forwards	2.64 ± 0.19
	Backs	2.63 ± 0.13
Gabbett et al. [95]	*Rugby, gender NA, club, 23.6 ± 5.3 years*	
	Trial #1	2.39 ± 0.17
	Trial #2	2.37 ± 0.16
Fernandez-Fernandez et al. [96]	*Tennis, male, elite 12.5 ± 0.3 years*	
	Pre-train	2.95 ± 0.2
	Post-train	2.86 ± 0.2
	Control group	2.92 ± 0.1
Fernandez-Fernandez et al. [97]	*Tennis, gender NA, elite, 14.8 ± 0.1 years*	
	Pre-train, drills	2.88 ± 0.17
	Post-train, drills	2.86 ± 0.17
	Pre-train, mixed	3.03 ± 0.08
	Post-train, mixed	2.95 ± 0.11
Spiteri et al. [58]	*Basketball, female, professional, 24.2 ± 2.5*	
	Profile	2.69 ± 0.28
Sharma et al. [98]	*Field hockey, male, 15.7 ± 1.6*	
	Pre-train	3.05 ± 0.15
	Post-train	2.95 ± 0.21
Chatzopoulos et al. [99]	*High school athletes, female, 17.3 ± 0.5 years*	
	Static stretch warm-up	3.11 ± 0.21
	Dynamic stretch warm-up	3.00 ± 0.20
Duking et al. [100]	*Team sport athletes, male and female, 19 ± 3 years*	
	Trial #1	2.6 ± 0.1
	Trial #2	2.5 ± 0.1
Yanci et al. [101]	*Competitive youth runners*	
	Under 8 boys/girls	3.14 ± 0.31/3.12 ± 0.21
	Under 10 boys/girls	2.92 ± 0.37/2.84 ± 0.16
	Under 12 boys/girls	2.76 ± 0.17/2.77 ± 0.16
	Under 14 boys/girls	2.68 ± 0.17/2.80 ± 0.27
	Under 16 boys/girls	2.62 ± 0.16/2.71 ± 0.14
Whitehead et al. [102]	*Healthy volunteers, male, 21.3 ± 1.8 years*	
	Plyometric train	2.6 ± 0.2
	Resistance train	3.8 ± 0.3
	Control group	4.7 ± 0.5

NA not available

hence, running speed) is progressively increased until the athlete reaches volitional exhaustion and can no longer maintain pace with the audio signals, indicated when three beeps are missed in a row. The athletes' level and number of shuttles reached before they were unable to keep up with the audio recording are recorded (Table 20.7). The athletes' VO_2max is estimated using the equation described by Ramsbottom et al. [103]:

$$VO_2\ max = (5.857 \times \text{speed on the last stage}) - 19.458$$

The results may be analyzed according to gender and age-matched percentile groups published by the American College of Sports Medicine [104] (Table 20.8), or by the more recent data published in a systematic review by Tomkinson et al. [105] of 1,142,026 subjects aged 9–17 years from 50 countries (Table 20.9). Samples of published results according to sport and gender are provided in Table 20.10. The MSFT has been used to determine cardiovascular fitness levels in basketball [32, 47], soccer [33, 86, 106–113], volleyball [35, 49, 114–116, 125], rugby [94, 117–120], tennis [121, 122], and in youth athletes [123, 124]. Test-retest reliability of the MSFT has been reported by others to be excellent, with ICCs ≥0.90 [19, 126–128]. The validity of this test in regard to estimating cardiorespiratory fitness has also been calculated to be acceptable [129].

Fig. 20.7 Course used for the 20-m multistage fitness test (cones #1 and #2 only) and the 20-m Yo-Yo intermittent test (cones #1, #2, and #3) (From Barber-Westin and Noyes [28])

Table 20.7 Predicted peak oxygen uptake values for multistage fitness test[a]

Level	No. shuttles	Predicted VO_2max	Level	No. shuttles	Predicted VO_2max
4	2	26.8	13	2	57.6
4	4	27.6	13	4	58.2
4	6	28.3	13	6	58.7
4	9	29.5	13	8	59.3
5	2	30.2	13	10	59.8
5	4	31.0	13	13	60.6
5	6	31.8	14	2	61.1
5	9	32.9	14	4	61.7
6	2	33.6	14	6	62.2
6	4	34.3	14	8	62.7
6	6	35.0	14	10	63.2
6	8	35.7	14	13	64.0
6	9	36.4	15	2	64.6
7	2	37.1	15	4	65.1
7	4	37.8	15	6	65.6
7	6	38.5	15	8	66.2
7	8	39.2	15	10	66.7
7	10	39.9	15	13	67.5
8	2	40.5	16	2	68.0
8	4	41.1	16	4	68.5
8	6	41.8	16	6	69.0
8	8	42.4	16	8	69.5
8	10	43.3	16	10	69.9
9	2	43.9	16	12	70.5
9	4	44.5	16	14	70.9
9	6	45.2	17	2	71.4
9	8	45.8	17	4	71.9
9	11	46.8	17	6	72.4
10	2	47.4	17	8	72.9
10	4	48.0	17	10	73.4
10	6	48.7	17	12	73.9
10	8	49.3	17	14	74.4
10	11	50.2	18	2	74.8
11	2	50.8	18	4	75.3
11	4	51.4	18	6	75.8
11	6	51.9	18	8	76.2
11	8	52.5	18	10	76.7
11	10	53.1	18	12	77.2
11	12	53.7	18	15	77.9
12	2	54.3			
12	4	54.8			
12	6	55.4			
12	8	56.0			
12	10	56.5			
12	12	57.1			

[a]From the Department of Physical Education and Sports Science, Loughborough University, 1987

Table 20.8 Interpretation of predicted peak oxygen uptake values for multistage fitness test according to the American College of Sports Medicine[a]

Age (year)	Gender	Very poor	Poor	Fair	Good	Excellent	Superior
13–19	Females	<25.0	25.0–30.9	31.0–34.9	35.0–38.9	39.0–41.9	>41.9
	Males	<35.0	35.0–38.3	38.4–45.1	45.2–50.9	51.0–55.9	>55.9
20–29	Females	<23.6	23.6–28.9	29.0–32.9	33.0–36.9	37.0–41.0	>41.0
	Males	<33.0	33.0–36.4	36.5–42.4	42.5–46.4	46.5–52.4	>52.4
30–39	Females	<22.8	22.8–26.9	27.0–31.4	31.5–35.6	35.7–40.0	>40.0
	Males	<31.5	31.5–35.4	35.5–40.9	41.0–44.9	45.0–49.4	>49.4
40–49	Females	<21.0	21.0–24.4	24.5–28.9	29.0–32.8	32.9–36.9	>36.9
	Males	<30.2	30.2–33.5	33.6–38.9	39.0–43.7	43.8–48.0	>48.0
50–59	Females	<20.2	20.2–22.7	22.8–26.9	27.0–31.4	31.5–35.7	>35.7
	Males	<26.1	26.1–30.9	31.0–35.7	35.8–40.9	41.0–45.3	>45.3
60+	Females	<17.5	17.5–20.1	20.2–24.4	24.5–30.2	30.3–31.4	>31.4
	Males	<20.5	20.5–26.0	26.1–32.2	32.3–36.4	36.5–44.2	>44.2

Printed in Advance Fitness Assessment and Exercise Prescription, 3rd Edition, Vivian H. Heyward, 1998, p. 48
[a]From The Physical Fitness Specialist Certification Manual, The Cooper Institute for Aerobics Research, Dallas, X, revised 1997

Table 20.9 Predicted maximum oxygen uptake values for multistage fitness test percentiles according to age and gender in 1,142,026 subjects aged 9–17 years from 177 studies[a]

Age (year)	P 5	P 10	P 20	P 30	P 40	P 50	P 60	P 70	P 80	P 90
Boys										
9	41.7	43.1	44.8	46.1	47.1	48.1	49.1	50.2	51.5	53.2
10	39.7	41.3	43.2	44.6	45.8	46.9	48	49.2	50.6	52.5
11	37.7	39.5	41.7	43.2	44.6	45.8	47.0	48.4	49.9	52.1
12	36.0	38.0	40.5	42.3	43.8	45.2	46.7	48.2	50.0	52.4
13	34.6	36.9	39.7	41.7	43.4	45.0	46.6	48.3	50.3	53.1
14	33.3	35.8	38.8	41.0	42.9	44.6	46.4	48.3	50.5	53.5
15	31.8	34.5	37.8	40.1	42.1	44.0	45.9	47.9	50.2	53.4
16	30.4	33.2	36.6	39.1	41.3	43.2	45.2	47.3	49.8	53.3
17	28.9	32.0	35.6	38.2	40.5	42.6	44.7	46.9	49.5	53.2
Girls										
9	41.3	42.5	44.0	45.0	45.9	46.7	47.5	48.4	49.4	50.8
10	39.0	40.4	42.0	43.2	44.2	45.1	46.0	47.0	48.2	49.8
11	36.8	38.3	40.1	41.4	42.5	43.5	44.5	45.7	47.0	48.7
12	34.6	36.2	38.2	39.6	40.8	42.0	43.1	44.3	45.7	47.7
13	32.6	34.3	36.4	37.9	39.2	40.4	41.6	42.9	44.4	46.5
14	30.6	32.4	34.6	36.2	37.6	38.8	40.1	41.4	43.0	45.2
15	28.7	30.5	32.8	34.5	35.9	37.2	38.5	39.9	41.6	43.9
16	26.7	28.7	31.1	32.8	34.2	35.6	37.0	38.4	40.2	42.5
17	24.7	26.8	29.3	31.1	32.6	34.1	35.5	37.0	38.8	41.3

P percentile
[a]From Tomkinson et al. [105]

Table 20.10 Sample results of predicted VO_2max from multistage fitness testing

Study	Cohort details (age)	VO_2max (mL kg^{-1} min^{-1})
Noyes et al. [32]	*Basketball, female, high school, 14–17 years*	
	Pre-train	34.6 ± 4.5
	Post-train	39.5 ± 5.7
Ben Abdelkrim et al. [47]	*Basketball, male, elite, 18.2 ± 0.5 years*	
	Profile	53.18 ± 2.7
Andersen [86]	*Soccer, female, collegiate, 19.7 ± 1.2 years*	
	Profile	68.81 ± 12.1
Noyes et al. [33]	*Soccer, female, high school, 12–18 years*	
	Pre-train	37.9 ± 4.5
	Post-train	40.1 ± 4.7
Higino et al. [106]	*Soccer, male, elite, 16.7 ± 0.7 years*	
	Profile	50.67 ± 3.6
Meckel et al. [107]	*Soccer, male, elite, 16–18 years*	
	Profile	54.1 ± 3.1
Nassis et al. [108]	*Soccer, male semi-pro, 22.8 ± 2.5 years*	
	Profile	50.7 ± 3.1
Caldwell et al. [109]	*Soccer, male, semi-pro, 24 ± 4.4 years*	
	Profile	58.0 ± 1.9
Hill-Haas et al. [110]	*Soccer, male, elite, 14.6 ± 0.9 years*	
	Small-sided trained	60.2 ± 4.6
	Generic trained	59.3 ± 4.5
Aziz et al. [111]	*Soccer, male, elite, 17.7 ± 0.4 years*	
	Profile	57.8 ± 5.0
Gabbett et al. [112]	*Soccer, female, elite, 18.3 ± 2.8 years*	
	Trained	48.8 ± 3.6
	Control	52.1 ± 5.1
Guy et al. [113]	*Soccer, male recreational*	
	Experimental, age 26.6 ± 8.2 years	44.0 ± 6.7
	Placebo trained, age 23.9 ± 6.7 years	42.9 ± 8.7
	Control, age 21.3 ± 4.9 years	46.3 ± 6.2
Noyes et al. [35]	*Volleyball, high school females, 14.5 ± 1.0 years*	
	Pre-train	39.4 ± 4.8
	Post-train	41.4 ± 4.0
Gabbett et al. [114]	*Volleyball, male and female, 15.6 ± 0.1 years*	
	Instructional trained	45.7 ± 2.0
	Skill-based conditioned	43.8 ± 2.0
Gabbett et al. [49]	*Volleyball, 15.6 ± 0.1 years*	
	National, male	50.6 ±1.4
	National, female	41.2 ± 0.9
	State, male	49.8 ± 1.1
	State, female	39.3 ± 0.7
	Novice, male	41.2 ± 1.2
	Novice, female	37.0 ± 0.8
Gabbett et al. [115]	*Volleyball, gender NA, 15.5 ± 0.2 years*	
	Pre-train	40.8 ± 1.1
	Post-train	43.2 ± 1.1
Duncan et al. [116]	*Volleyball, male, elite, 17.5 ± 0.5 years*	
	Setters	46.9 ± 4.9
	Hitters	51.1 ± 3.7
	Centers	50.4 ± 3.7
	Opposites	48.3 ± 6.7
Scott et al. [117]	*Rugby, male, elite, 25 ± 4 years and junior-elite, 19 ± 0.6 years*	
	Profile	51.2 ± 4.1
Gabbett et al. [118]	*Rugby, male, semipro, 24 ± 3 years*	
	1st grade	51.9 ± 3.3
	2nd grade	51.1 ± 4.5
Gabbett et al. [119]	*Rugby, male*	
	Junior, age 16–17 years	46.3
	Senior, age 23–27 years	44.9
Gabbett et al. [94]	*Rugby, female, elite, 18.9 ± 5.7 years*	
	Forwards	32.2 ± 4.4
	Backs	35.3 ± 3.4
	Hit-up forwards	31.2 ± 3.3
	Adjustables	36.2 ± 4.6
	Outside backs	34.5 ± 2.2
Till et al. [120]	*Rugby, league*	
	Under 13	47.9 ± 5.4
	Under 14	50.1 ± 4.7
	Under 15	51.3 ± 4.6
Fargeas-Gluck and Leger [121]	*Tennis, elite, male and female, 12.9 ± 0.3 years*	
	Profile	54.2 ± 5.9
Brechbuhl et al. [122]	*Tennis, elite, male and female, 16.8 ± 0.9 years*	
	Profile	56.5 ± 5.6
Ballester et al. [123]	*Children, male and female, 11.0 ± 0.2 years*	
	Soccer, elite	50.5
	Track and field, club	49.3
	No sports	47.6
Smith et al. [124]	*Athletes, high school, 14.4 ± 1.6 years*	
	Male	43.65 ± 8.3
	Female	33.14 ± 4.7

NA not available

20.4.2 Intermittent Recovery: Yo-Yo Test Level 1 and Level 2

The Yo-Yo recovery test is conducted in a manner similar to the MSFT; however, periods of 10-s of rest are incorporated after each 2 × 20-m shuttle run until the athlete is exhausted. There are two test levels: level 1 (Yo-Yo IR1) and level 2 (Yo-Yo IR2). Level 1 is designated for lesser trained individuals and level 2 is appropriate for elite and highly trained athletes. The equipment required are commercially available software (from which a CD may be made), or a commercially available audio CD, and a CD player. Three cones are used to mark the course as shown in Fig. 20.7. The athlete begins with their toes behind the designated starting cone (cone #1 in Fig. 20.7). The second cone is located 20 m away. The athlete is instructed that, on the "go" command (which is an audible beep on the CD), they are to run to the second cone and then return to the starting position when signaled by the recorded beep. They may jog or walk around the third cone and then turn back to the starting cone during a 10-s rest period. The athlete continues to perform this pattern, keeping in time with the series of signals (beeps) on the CD. The frequency of the audible signals (and hence, running speed) is progressively increased until the athlete reaches volitional exhaustion and can no longer maintain pace with the audio signals. The athletes' level and number of shuttles reached before they were unable to keep up with the audio recording are recorded.

The level 1 test usually takes 6–20 min to complete and level 2, 2–10 min. The athlete's score is the total distance covered before they are unable to keep up with the recording (Tables 20.11 and 20.12). Although calculations exist for estimating VO_2max using the Yo-Yo test, investigators do not recommend this analysis due to high subject variability previously reported [20]. Instead, it is recommended that the total distance recorded be used to evaluate an athlete's ability to repeatedly perform intermittent exercise. Reliability for these tests is high, with ICCs >0.90 [131, 132].

These tests have been studied extensively in athletes participating in recreational team sports, badminton, basketball, soccer, rugby, team handball, volleyball, and field hockey (Table 20.13) [20, 93, 133–141, 143–148]. Several studies have reported high reliability, reproducibility, and sensitivity of the Yo-Yo tests to detect change resulting from training programs. These tests correlate with player position and performance during soccer games and distinguish various levels of athletes (i.e., professional, sub-elite, recreational) [20, 110, 136, 138, 149–152].

Table 20.11 Yo-Yo intermittent recovery test level 1 protocol [130]

Stage	Speed (km/h^{-1})	Shuttle bouts 2 × 20-m	Split distance (m)	Accumulated distance (m)
1	10.0	1	40	40
2	12.0	1	40	80
3	13.0	2	80	160
4	13.5	3	120	280
5	14.0	4	160	440
6	14.5	8	320	760
7	15.0	8	320	1080
8	15.5	8	320	1400
9	16.0	8	320	1720
10	16.5	8	320	2040
11	17.0	8	320	2360
12	17.5	8	320	2680
13	18.0	8	320	3000
14	18.5	8	320	3320
15	19.0	8	320	3640

Table 20.12 Yo-Yo intermittent recovery test level 2 protocol [130]

Stage	Speed (km/h^{-1})	Shuttle bouts 2 × 20-m	Split distance (m)	Accumulated distance (m)
1	11.5	10	200	200
2	12.0	11	220	420
3	12.5	11	220	640
4	13.0	11	220	860
5	13.5	12	240	1100
6	14.0	12	240	1340
7	14.5	13	260	1600
8	15.0	13	260	1860
9	15.5	13	260	2120
10	16.0	14	280	2400
11	16.5	14	280	2680
12	17.0	15	300	2980
13	17.5	15	300	3280
14	18.0	16	320	3600

Table 20.13 Sample results of the Yo-Yo intermittent recovery test according to sport and gender

Study	Cohort details (age)	Yo-Yo IR1 test (m)	Yo-Yo IR2 test (m)
Bangsbo et al. [20]	*Badminton, female, high-level*		
	Age 21 years	1200	NA
	Age 17 years	1080	NA
Castagna et al. [133]	*Basketball, male, club, 16.8 ± 2.0 years*		
	Profile	1678 ± 397	NA
Bangsbo et al. [20]	*Basketball, male, junior players professional club, age NA*		
	Profile	NA	590
Klusemann et al. [134]	*Basketball, male and female adolescents*		
	Supervised trained: pre-train/post-train	822 ± 640/978 ± 528	NA
	Video trained: pre-train/post-train	797 ± 385/834 ± 414	NA
	Control: pre-train/post-train	916 ± 370/862 ± 363	NA
Lockie et al. [135]	*Soccer, female, collegiate, 20.2 ± 1.2 year*		
	Profile	1666 ± 473	533 ± 164
Bradley et al. [136]	*Soccer, female*		
	European national elite teams, age 23 ± 2 years	NA	1774 ± 532
	Elite U-20, age 19 ± 1	NA	1490 ± 447
	Recreational, age 22 ± 3 years	NA	1261 ± 449
	Sub-elite, age 23 ± 4 years	NA	994 ± 373
Bangsbo et al. [20]	*Soccer, male, age NA*		
	Top-elite	2420	NA
	Moderate-elite	2190	NA
	Sub-elite	2030	NA
Bangsbo et al. [20]	*Soccer, female, age NA*		
	Top-elite	1600	NA
	Moderate-elite	1360	NA
	Sub-elite	1160	NA
Rampinini et al. [137]	*Soccer, male, 25 ± 5 years*		
	Professional	2231 ± 294	958 ± 99
	Amateur	1827 ± 292	613 ± 125
Fanchini et al. [138]	*Soccer, male, semi-pro, 24 ± 6 years*		
	Pre-season	1695 ± 243	NA
	Post-season	2385 ± 412	NA
Nicks et al. [139]	*Soccer, male and female, collegiate, 19.8 ± 0.9 years*		
	Pre-train	1250 ± 351	NA
	Post-train	1466 ± 486	NA
Flatt and Esco [140]	*Soccer, female, collegiate, 22 ± 2.3 years*		
	Profile	1250 ± 247	NA
Dupont et al. [141]	*Soccer, male, amateur, 23.2 ± 3.5 years*		
	Profile	2034 ± 367	NA
Lockie et al. [142]	*Soccer, male, collegiate, 20.4 ± 1.5 years*		
	Defenders	NA	962 ± 294
	Midfielders	NA	1384 ± 318
	Forwards	NA	880 ± 365
Makhlouf et al. [143]	*Soccer, male, elite, 13.7 ± 0.5 years*		
	Endurance-strength: pre-train/post-train	931 ± 177/1663 ± 219	NA
	Strength-endurance: pre-train/post-train	1034 ± 308/1642 ± 339	NA
	Strength-endurance alternated: pre-train/post-train	974 ± 273/1505 ± 306	NA
	Control pre-train/post-train	945 ± 260/1234 ± 330	NA
Moss et al. [144]	*Handball, female*		
	Non-elite, age 15.7 ± 1.3 years	906 ± 324	NA
	Elite, age 15.8 ± 1.3 years	935 ± 394	NA
	Top-elite, age 17.1 ± 1.1 years	1663 ± 327	NA

Table 20.13 (continued)

Study	Cohort details (age)	Yo-Yo IR1 test (m)	Yo-Yo IR2 test (m)
Souhail et al. [145]	*Handball, male, 14.3 ± 0.5 years*		
	Profile	1831 ± 373	NA
Jones et al. [93]	*Rugby, female, elite, 23.5 ± 4.1 years*		
	Backs	728 ± 154	NA
	Forwards	610 ± 292	NA
Purkhus et al. [146]	*Volleyball, female, elite, 19 ± 5 years*		
	High-intensity: pre-train/post-train	NA	191 ± 43/215 ± 32
	Control: pre-train/post-train	NA	193 ± 62/204 ± 63
Vescovi [147]	*Field hockey, female, national*		
	U21 team	1480 ± 332	NA
	U17 team	1068 ± 220	NA
Serpiello et al. [148]	*Recreational athletes, male and female, 22.3 ± 4.1 years*		
	Pre-train	1305 ± 709	NA
	Post repeated-sprint train	1400 ± 715	NA

Yo-Yo IR1 Yo-Yo intermittent recovery level 1, *Yo-Yo IR2* Yo-Yo intermittent recovery level 2, *NA* not available

References

1. Boden BP, Torg JS, Knowles SB, Hewett TE. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. Am J Sports Med. 2009;37(2):252–9. https://doi.org/10.1177/0363546508328107.
2. Krosshaug T, Nakamae A, Boden BP, Engebretsen L, Smith G, Slauterbeck JR, Hewett TE, Bahr R. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. Am J Sports Med. 2007;35(3):359–67.
3. Sheehan FT, Sipprell WH, Boden BP. Dynamic sagittal plane trunk control during anterior cruciate ligament injury. Am J Sports Med. 2012;40(5):1068–74. https://doi.org/10.1177/0363546512437850.
4. Stewart PF, Turner AN, Miller SC. Reliability, factorial validity, and interrelationships of five commonly used change of direction speed tests. Scand J Med Sci Sports. 2014;24(3):500–6. https://doi.org/10.1111/sms.12019.
5. Vescovi JD, McGuigan MR. Relationships between sprinting, agility, and jump ability in female athletes. J Sports Sci. 2008;26(1):97–107. https://doi.org/10.1080/02640410701348644.
6. Pauole K, Madole K, Garhammer J, Lacourse M, Rozenek R. Reliability and validity of the t-test as a measure of agility, leg power, and leg speed in college-aged men and women. J Strength Cond Res. 2000;14(4):443–50.
7. Munro AG, Herrington LC. Between-session reliability of four hop tests and the agility T-test. J Strength Cond Res. 2011;25(5):1470–7. https://doi.org/10.1519/JSC.0b013e3181d83335.
8. Hastad DN, Lacy AC. Measurement and evaluation in physical education and exercise science. 2nd ed. Scottsdale: Gorsuch Scarisbric; 1994.
9. Draper J. The 505 test: a test for agility in horizontal plane. Aust J Sci Med Sport. 1985;17(1):15–8.
10. Harman EA. Principles of test selection and administration. In: Beachle TR, Earle RW, editors. Essentials of strength training and conditioning. 3rd ed. Champaign: Human Kinetics; 2008. p. 238–46.
11. Jones MT, Lorenzo DC. Assessment of power, speed, and agility in athletic, preadolescent youth. J Sports Med Phys Fitness. 2013;53(6):693–700.
12. Delextrat A, Cohen D. Strength, power, speed, and agility of women basketball players according to playing position. J Strength Cond Res. 2009;23(7):1974–81. https://doi.org/10.1519/JSC.0b013e3181b86a7e.
13. Delextrat A, Grosgeorge B, Bieuzen F. Determinants of performance in a new test of planned agility for young elite basketball players. Int J Sports Physiol Perform. 2015;10(2):160–5. https://doi.org/10.1123/ijspp.2014-0097.
14. Jarvis S, Sullivan LO, Davies B, Wiltshire H, Baker JS. Interrelationships between measured running intensities and agility performance in subelite rugby union players. Res Sports Med. 2009;17(4):217–30. https://doi.org/10.1080/15438620903323892.
15. Little T, Williams AG. Specificity of acceleration, maximum speed, and agility in professional soccer players. J Strength Cond Res. 2005;19(1):76–8. https://doi.org/10.1519/14253.1.
16. Sheppard JM, Young WB. Agility literature review: classifications, training and testing. J Sports Sci. 2006;24(9):919–32. https://doi.org/10.1080/02640410500457109.
17. Sporis G, Jukic I, Milanovic L, Vucetic V. Reliability and factorial validity of agility tests for soccer players. J Strength Cond Res. 2010;24(3):679–86. https://doi.org/10.1519/JSC.0b013e3181c4d324.
18. Knapik JJ, Sharp MA, Canham-Chervak M, Hauret K, Patton JF, Jones BH. Risk factors for

training-related injuries among men and women in basic combat training. Med Sci Sports Exerc. 2001;33(6):946–54.
19. Leger LA, Lambert J. A maximal multistage 20-m shuttle run test to predict VO2 max. Eur J Appl Physiol Occup Physiol. 1982;49(1):1–12.
20. Bangsbo J, Iaia FM, Krustrup P. The Yo-Yo intermittent recovery test: a useful tool for evaluation of physical performance in intermittent sports. Sports Med. 2008;38(1):37–51.
21. Aziz AR, Mukherjee S, Chia MY, Teh KC. Relationship between measured maximal oxygen uptake and aerobic endurance performance with running repeated sprint ability in young elite soccer players. J Sports Med Phys Fitness. 2007;47(4):401–7.
22. Castagna C, Abt G, D'Ottavio S. Competitive-level differences in Yo-Yo intermittent recovery and twelve minute run test performance in soccer referees. J Strength Cond Res. 2005;19(4):805–9. https://doi.org/10.1519/R-14473.1.
23. Aziz AR, Tan FHY, Teh KC. A pilot study comparing two field tests with the treadmill run test in soccer players. J Sports Sci Med. 2005;4:105–12.
24. Turner A, Walker S, Stembridge M, Coneyworth P, Reed G, Birdsey L, Barter P, Moody J. A testing battery for the assessment of fitness in soccer players. Strength Cond J. 2011;33(5):29–39.
25. Noyes FR, Barber-Westin SD, Fleckenstein C, Walsh C, West J. The drop-jump screening test: difference in lower limb control by gender and effect of neuromuscular training in female athletes. Am J Sports Med. 2005;33(2):197–207.
26. Redler LH, Watling JP, Dennis ER, Swart E, Ahmad CS. Reliability of a field-based drop vertical jump screening test for ACL injury risk assessment. Phys Sportsmed. 2016;44(1):46–52. https://doi.org/10.1080/00913847.2016.1131107.
27. Sigward SM, Havens KL, Powers CM. Knee separation distance and lower extremity kinematics during a drop land: implications for clinical screening. J Athl Train. 2011;46(5):471–5.
28. Barber-Westin SD, Noyes FR. Testing for neuromuscular problems and athletic performance. In: ACL injuries in the female athlete. Causes, impacts, and conditioning programs. 2nd ed. New York: Springer; 2018. p. 289–333.
29. Huston LJ, Vibert B, Ashton-Miller JA, Wojtys EM. Gender differences in knee angle when landing from a drop-jump. Am J Knee Surg. 2001;14(4):215–9.
30. Chaudhari AM, Hearn BK, Leveille LA, Johnson ER, Andriacchi TP. The effects of dynamic limb alignment on knee moments during single limb landing: Implications for the analysis of the non-contact injury to the anterior cruciate ligament. In: 2003 Summer Bioengineering Conference, Key Biscayne, FL, June 25–29, 2003; 2003.
31. Khuu S, Musalem LL, Beach TA. Verbal instructions acutely affect drop vertical jump biomechanics--implications for athletic performance and injury risk assessments. J Strength Cond Res. 2015;29(10):2816–26. https://doi.org/10.1519/JSC.0000000000000938.
32. Noyes FR, Barber-Westin SD, Smith ST, Campbell T, Garrison TT. A training program to improve neuromuscular and performance indices in female high school basketball players. J Strength Cond Res. 2012;26(3):709–19. https://doi.org/10.1519/JSC.0b013e318228194c.
33. Noyes FR, Barber-Westin SD, Tutalo Smith ST, Campbell T. A training program to improve neuromuscular and performance indices in female high school soccer players. J Strength Cond Res. 2013;27(2):340–51. https://doi.org/10.1519/JSC.0b013e31825423d9.
34. Rodriguez C, Echegoyen S, Aoyama T. The effects of "Prevent Injury and Enhance Performance Program" in a female soccer team. J Sports Med Phys Fitness. 2017. https://doi.org/10.23736/S0022-4707.17.07024-4.
35. Noyes FR, Barber-Westin SD, Smith ST, Campbell T. A training program to improve neuromuscular indices in female high school volleyball players. J Strength Cond Res. 2011;25(8):2151–60. https://doi.org/10.1519/JSC.0b013e3181f906ef.
36. Noyes FR, Barber-Westin SD. Neuromuscular retraining in female adolescent athletes: effect on athletic performance indices and noncontact anterior cruciate ligament injury rates. Sports. 2015;3:56–76. https://doi.org/10.3390/sports3020056.
37. Barendrecht M, Lezeman HC, Duysens J, Smits-Engelsman BC. Neuromuscular training improves knee kinematics, in particular in valgus aligned adolescent team handball players of both sexes. J Strength Cond Res. 2011;25(3):575–84. https://doi.org/10.1519/JSC.0b013e3182023bc7.
38. Chimera NJ, Kremer K. Sportsmetrics training improves power and landing in high school rowers. Int J Sports Phys Ther. 2016;11(1):44–53.
39. Pollard CD, Sigward SM, Powers CM. Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. Clin J Sport Med. 2007;17(1):38–42. https://doi.org/10.1097/JSM.0b013e3180305de8.
40. Cortes N, Onate J, Van Lunen B. Pivot task increases knee frontal plane loading compared with side-step and drop-jump. J Sports Sci. 2011;29(1):83–92. https://doi.org/10.1080/02640414.2010.523087.
41. Jones PA, Herrington LC, Munro AG, Graham-Smith P. Is there a relationship between landing, cutting, and pivoting tasks in terms of the characteristics of dynamic valgus? Am J Sports Med. 2014;42(9):2095–102. https://doi.org/10.1177/0363546514539446.
42. McLean SG, Huang X, van den Bogert AJ. Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. Clin Biomech. 2005;20(8):863–70. https://doi.org/10.1016/j.clinbiomech.2005.05.007.

43. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. Clin Biomech. 2001;16(5):438–45.
44. Sigward SM, Powers CM. The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. Clin Biomech. 2006;21(1):41–8. https://doi.org/10.1016/j.clinbiomech.2005.08.001.
45. Semenick D. The T test. NCSA J. 1990;12(1):36–7.
46. Asadi A, Ramirez-Campillo R, Meylan C, Nakamura FY, Canas-Jamett R, Izquierdo M. Effects of volume-based overload plyometric training on maximal-intensity exercise adaptations in young basketball players. J Sports Med Phys Fitness. 2017;57(12):1557–63. https://doi.org/10.23736/s0022-4707.16.06640-8.
47. Ben Abdelkrim N, Castagna C, Jabri I, Battikh T, El Fazaa S, El Ati J. Activity profile and physiological requirements of junior elite basketball players in relation to aerobic-anaerobic fitness. J Strength Cond Res. 2010;24(9):2330–42. https://doi.org/10.1519/JSC.0b013e3181e381c1.
48. Delextrat A, Cohen D. Physiological testing of basketball players: toward a standard evaluation of anaerobic fitness. J Strength Cond Res. 2008;22(4):1066–72. https://doi.org/10.1519/JSC.0b013e3181739d9b.
49. Gabbett T, Georgieff B. Physiological and anthropometric characteristics of Australian junior national, state, and novice volleyball players. J Strength Cond Res. 2007;21(3):902–8. https://doi.org/10.1519/R-20616.1.
50. Hoffman JR, Ratamess NA, Neese KL, Ross RE, Kang J, Magrelli JF, Faigenbaum AD. Physical performance characteristics in National Collegiate Athletic Association Division III champion female lacrosse athletes. J Strength Cond Res. 2009;23(5):1524–9. https://doi.org/10.1519/JSC.0b013e3181b3391d.
51. Khodaei K, Mohammadi A, Badri N. A comparison of assisted, resisted, and common plyometric training modes to enhance sprint and agility performance. J Sports Med Phys Fitness. 2017;57(10):1237–44. https://doi.org/10.23736/s0022-4707.17.06901-8.
52. Lidor R, Ziv G. Physical and physiological attributes of female volleyball players--a review. J Strength Cond Res. 2010;24(7):1963–73. https://doi.org/10.1519/JSC.0b013e3181ddf835.
53. McFarland IT, Dawes JJ, Elder CL, Lockie RG. Relationship of two vertical jumping tests to sprint and change of direction speed among male and female collegiate soccer players. Sports. 2016;4(1). https://doi.org/10.3390/sports4010011.
54. Miller MG, Herniman JJ, Ricard MD, Cheatham CC, Michael TJ. The effects of a 6-week plyometric training program on agility. J Sports Sci Med. 2006;5(3):459–65.
55. Myrick S. Injury prevention and performance enhancement: a training program for basketball. Conn Med. 2007;71(1):5–8.
56. Negra Y, Chaabene H, Hammami M, Amara S, Sammoud S, Mkaouer B, Hachana Y. Agility in young athletes: is it a different ability from speed and power? J Strength Cond Res. 2017;31(3):727–35. https://doi.org/10.1519/jsc.0000000000001543.
57. Sekulic D, Uljevic O, Peric M, Spasic M, Kondric M. Reliability and factorial validity of non-specific and tennis-specific pre-planned agility tests; preliminary analysis. J Hum Kinet. 2017;55:107–16. https://doi.org/10.1515/hukin-2017-0010.
58. Spiteri T, Nimphius S, Hart NH, Specos C, Sheppard JM, Newton RU. Contribution of strength characteristics to change of direction and agility performance in female basketball athletes. J Strength Cond Res. 2014;28(9):2415–23. https://doi.org/10.1519/JSC.0000000000000547.
59. Towlson C, Cobley S, Parkin G, Lovell R. When does the influence of maturation on anthropometric and physical fitness characteristics increase and subside? Scand J Med Sci Sports. 2018;28(8):1946–55. https://doi.org/10.1111/sms.13198.
60. Sassi RH, Dardouri W, Yahmed MH, Gmada N, Mahfoudhi ME, Gharbi Z. Relative and absolute reliability of a modified agility T-test and its relationship with vertical jump and straight sprint. J Strength Cond Res. 2009;23(6):1644–51. https://doi.org/10.1519/JSC.0b013e3181b425d2.
61. Raya MA, Gailey RS, Gaunaurd IA, Jayne DM, Campbell SM, Gagne E, Manrique PG, Muller DG, Tucker C. Comparison of three agility tests with male servicemembers: edgren side step test, T-Test, and Illinois agility test. J Rehabil Res Dev. 2013;50(7):951–60. https://doi.org/10.1682/jrrd.2012.05.0096.
62. Kutlu M, Yapici H, Yilmaz A. Reliability and validity of a new test of agility and skill for female amateur soccer players. J Hum Kinet. 2017;56:219–27. https://doi.org/10.1515/hukin-2017-0039.
63. Arede J, Vaz R, Franceschi A, Gonzalo-Skok O, Leite N. Effects of a combined strength and conditioning training program on physical abilities in adolescent male basketball players. J Sports Med Phys Fitness. 2018. https://doi.org/10.23736/s0022-4707.18.08961-2.
64. Bishop C, Turner AN, Cree J, Maloney S, Marshall J, Jarvis P. Postactivation potentiation and change of direction speed in elite academy rugby players. J Strength Cond Res. 2017;33(6):1551–6. https://doi.org/10.1519/JSC.0000000000001834.
65. Collins KS, Coburn JW, Galpin AJ, Lockie RG. Relationships and reliability between a drive block test and traditional football performance tests in high school offensive line players. J Strength Cond Res. 2018;32(12):3423–32. https://doi.org/10.1519/jsc.0000000000002757.
66. Fitzgerald CF, Jensen RL. A comparison of the national football league's annual national football league combine 1999-2000 to 2015-2016. J Strength Cond Res. 2018. https://doi.org/10.1519/jsc.0000000000002682.

67. Jones MT, Matthews TD, Murray M, Van Raalte J, Jensen BE. Psychological correlates of performance in female athletes during a 12-week off-season strength and conditioning program. J Strength Cond Res. 2010;24(3):619–28. https://doi.org/10.1519/JSC.0b013e3181cc23c3.
68. Lockie RG, Moreno MR, Lazar A, Orjalo AJ, Giuliano DV, Risso FG, Davis DL, Crelling JB, Lockwood JR, Jalilvand F. The physical and athletic performance characteristics of division i collegiate female soccer players by position. J Strength Cond Res. 2018;32(2):334–43. https://doi.org/10.1519/JSC.0000000000001561.
69. Magal M, Smith RT, Dyer JJ, Hoffman JR. Seasonal variation in physical performance-related variables in male NCAA Division III soccer players. J Strength Cond Res. 2009;23(9):2555–9. https://doi.org/10.1519/JSC.0b013e3181b3ddbf.
70. Mann JB, Ivey PA, Mayhew JL, Schumacher RM, Brechue WF. Relationship between agility tests and short sprints: reliability and smallest worthwhile difference in national collegiate athletic association division-i football players. J Strength Cond Res. 2016;30(4):893–900. https://doi.org/10.1519/jsc.0000000000001329.
71. Vescovi JD, Rupf R, Brown TD, Marques MC. Physical performance characteristics of high-level female soccer players 12-21 years of age. Scand J Med Sci Sports. 2011;21(5):670–8. https://doi.org/10.1111/j.1600-0838.2009.01081.x.
72. Yuasa Y, Kurihara T, Isaka T. Relationship between toe muscular strength and the ability to change direction in athletes. J Hum Kinet. 2018;64:47–55. https://doi.org/10.1515/hukin-2017-0183.
73. McKay BD, Miramonti AA, Gillen ZM, Leutzinger TJ, Mendez AI, Jenkins NDM, Cramer JT. Normative reference values for high school-aged American football players. J Strength Cond Res. 2018. https://doi.org/10.1519/jsc.0000000000002532.
74. Amiri-Khorasani M, Sahebozamani M, Tabrizi KG, Yusof AB. Acute effect of different stretching methods on Illinois agility test in soccer players. J Strength Cond Res. 2010;24(10):2698–704. https://doi.org/10.1519/JSC.0b013e3181bf049c.
75. Daneshjoo A, Mokhtar AH, Rahnama N, Yusof A. Effects of the 11+ and harmoknee warm-up programs on physical performance measures in professional soccer players. J Sports Sci Med. 2013;12(3):489–96.
76. Fiorilli G, Iuliano E, Mitrotasios M, Pistone EM, Aquino G, Calcagno G, di Cagno A. Are change of direction speed and reactive agility useful for determining the optimal field position for young soccer players? J Sports Sci Med. 2017;16(2):247–53.
77. Gabbett TJ. Physiological characteristics of junior and senior rugby league players. Br J Sports Med. 2002;36(5):334–9.
78. Hachana Y, Chaabene H, Nabli MA, Attia A, Moualhi J, Farhat N, Elloumi M. Test-retest reliability, criterion-related validity, and minimal detectable change of the Illinois agility test in male team sport athletes. J Strength Cond Res. 2013;27(10):2752–9. https://doi.org/10.1519/JSC.0b013e3182890ac3.
79. Howard N, Stavrianeas S. In-season high-intensity interval training improves conditioning in high school soccer players. Int J Exerc Sci. 2017;10(5):713–20.
80. Keogh JW, Weber CL, Dalton CT. Evaluation of anthropometric, physiological, and skill-related tests for talent identification in female field hockey. Can J Appl Physiol. 2003;28(3):397–409.
81. Makhlouf I, Chaouachi A, Chaouachi M, Ben Othman A, Granacher U, Behm DG. Combination of agility and plyometric training provides similar training benefits as combined balance and plyometric training in young soccer players. Front Physiol. 2018;9:1611. https://doi.org/10.3389/fphys.2018.01611.
82. Negra Y, Chaabene H, Sammoud S, Bouguezzi R, Abbes MA, Hachana Y, Granacher U. Effects of plyometric training on physical fitness in prepuberal soccer athletes. Int J Sports Med. 2017;38(5):370–7. https://doi.org/10.1055/s-0042-122337.
83. Roopchand-Martin S, Lue-Chin P. Plyometric training improves power and agility in Jamaica's national netball team. West Indian Med J. 2010;59(2):182–7.
84. Vazini Taher A, Parnow A. Level of functional capacities following soccer-specific warm-up methods among elite collegiate soccer players. J Sports Med Phys Fitness. 2017;57(5):537–42. https://doi.org/10.23736/s0022-4707.16.06236-8.
85. Zarei M, Abbasi H, Daneshjoo A, Barghi TS, Rommers N, Faude O, Rossler R. Long-term effects of the 11+ warm-up injury prevention programme on physical performance in adolescent male football players: a cluster-randomised controlled trial. J Sports Sci. 2018;36(21):2447–54. https://doi.org/10.1080/02640414.2018.1462001.
86. Andersen E, Lockie RG, Dawes JJ. Relationship of absolute and relative lower-body strength to predictors of athletic performance in collegiate women soccer players. Sports. 2018;6(4):E106. https://doi.org/10.3390/sports6040106.
87. Lockie RG, Dawes JJ, Jones MT. Relationships between linear speed and lower-body power with change-of-direction speed in National Collegiate Athletic Association Divisions I and II women soccer athletes. Sports. 2018;6(2). https://doi.org/10.3390/sports6020030.
88. Emmonds S, Nicholson G, Beggs C, Jones B, Bissas A. Importance of physical qualities for speed and change of direction ability in elite female soccer players. J Strength Cond Res. 2017;33(6):1669–77. https://doi.org/10.1519/jsc.0000000000002114.
89. Beato M, Bianchi M, Coratella G, Merlini M, Drust B. Effects of plyometric and directional training on speed and jump performance in elite youth soccer players. J Strength Cond Res. 2018;32(2):289–96. https://doi.org/10.1519/JSC.0000000000002371.
90. Tomas M, Frantisek Z, Lucia M, Jaroslav T. Profile, correlation and structure of speed in youth elite soccer players. J Hum Kinet. 2014;40:149–59. https://doi.org/10.2478/hukin-2014-0017.

91. Dragijsky M, Maly T, Zahalka F, Kunzmann E, Hank M. Seasonal variation of agility, speed and endurance performance in young elite soccer players. Sports. 2017;5(1):12. https://doi.org/10.3390/sports5010012.
92. Darrall-Jones JD, Jones B, Till K. Anthropometric and physical profiles of English academy rugby union players. J Strength Cond Res. 2015;29(8):2086–96. https://doi.org/10.1519/jsc.0000000000000872.
93. Jones B, Emmonds S, Hind K, Nicholson G, Rutherford Z, Till K. Physical qualities of international female rugby league players by playing position. J Strength Cond Res. 2016;30(5):1333–40. https://doi.org/10.1519/JSC.0000000000001225.
94. Gabbett TJ. Physiological and anthropometric characteristics of elite women rugby league players. J Strength Cond Res. 2007;21(3):875–81. https://doi.org/10.1519/R-20466.1.
95. Gabbett TJ, Kelly JN, Sheppard JM. Speed, change of direction speed, and reactive agility of rugby league players. J Strength Cond Res. 2008;22(1):174–81. https://doi.org/10.1519/JSC.0b013e31815ef700.
96. Fernandez-Fernandez J, Saez de Villarreal E, Sanz-Rivas D, Moya M. The effects of 8-week plyometric training on physical performance in young tennis players. Pediatr Exerc Sci. 2016;28(1):77–86. https://doi.org/10.1123/pes.2015-0019.
97. Fernandez-Fernandez J, Sanz D, Sarabia JM, Moya M. The effects of sport-specific drills training or high-intensity interval training in young tennis players. Int J Sports Physiol Perform. 2017;12(1):90–8. https://doi.org/10.1123/ijspp.2015-0684.
98. Sharma HB, Kailashiya J. Effects of 6-week sprint-strength and agility training on body composition, cardiovascular, and physiological parameters of male field hockey players. J Strength Cond Res. 2018;32(4):894–901. https://doi.org/10.1519/jsc.0000000000002212.
99. Chatzopoulos D, Galazoulas C, Patikas D, Kotzamanidis C. Acute effects of static and dynamic stretching on balance, agility, reaction time and movement time. J Sports Sci Med. 2014;13(2):403–9.
100. Duking P, Born DP, Sperlich B. The speedcourt: reliability, usefulness, and validity of a new method to determine change-of-direction speed. Int J Sports Physiol Perform. 2016;11(1):130–4. https://doi.org/10.1123/ijspp.2015-0174.
101. Yanci J, Los Arcos A, Castillo D, Camara J. Sprinting, change of direction ability and horizontal jump performance in youth runners according to gender. J Hum Kinet. 2017;60:199–207. https://doi.org/10.1515/hukin-2017-0103.
102. Whitehead MT, Scheett TP, McGuigan MR, Martin AV. A comparison of the effects of short-term plyometric and resistance training on lower-body muscular performance. J Strength Cond Res. 2018;32(10):2743–9. https://doi.org/10.1519/jsc.0000000000002083.
103. Ramsbottom R, Brewer J, Williams C. A progressive shuttle run test to estimate maximal oxygen uptake. Br J Sports Med. 1988;22(4):141–4.
104. Franklin BA, Whaley MH, Howley ET. ACSM's guidelines for exercise testing and prescription. 6th ed. Baltimore: Lippincott Williams & Wilkins; 2009.
105. Tomkinson GR, Lang JJ, Tremblay MS, Dale M, LeBlanc AG, Belanger K, Ortega FB, Léger L. International normative 20 m shuttle run values from 1,142,026 children and youth representing 50 countries. Br J Sports Med. 2017;51(21):1545–54.
106. Higino WP, de Souza Sorroche A, de Mattos Falqueiro PG, Lima YCS, Higa CL. Determination of aerobic performance in youth soccer players: effect of direct and indirect methods. J Hum Kinet. 2017;56(1):109–18.
107. Meckel Y, Machnai O, Eliakim A. Relationship among repeated sprint tests, aerobic fitness, and anaerobic fitness in elite adolescent soccer players. J Strength Cond Res. 2009;23(1):163–9. https://doi.org/10.1519/JSC.0b013e31818b9651.
108. Nassis GP, Geladas ND, Soldatos Y, Sotiropoulos A, Bekris V, Souglis A. Relationship between the 20-m multistage shuttle run test and 2 soccer-specific field tests for the assessment of aerobic fitness in adult semi-professional soccer players. J Strength Cond Res. 2010;24(10):2693–7. https://doi.org/10.1519/JSC.0b013e3181bf0471.
109. Caldwell BP, Peters DM. Seasonal variation in physiological fitness of a semiprofessional soccer team. J Strength Cond Res. 2009;23(5):1370–7. https://doi.org/10.1519/JSC.0b013e3181a4e82f.
110. Hill-Haas SV, Coutts AJ, Rowsell GJ, Dawson BT. Generic versus small-sided game training in soccer. Int J Sports Med. 2009;30(9):636–42. https://doi.org/10.1055/s-0029-1220730.
111. Aziz AR, Chia MY, Teh KC. Measured maximal oxygen uptake in a multi-stage shuttle test and treadmill-run test in trained athletes. J Sports Med Phys Fitness. 2005;45(3):306–14.
112. Gabbett TJ, Carius J, Mulvey M. Does improved decision-making ability reduce the physiological demands of game-based activities in field sport athletes? J Strength Cond Res. 2008;22(6):2027–35. https://doi.org/10.1519/JSC.0b013e3181887f34.
113. Guy JH, Edwards AM, Deakin GB. Inspiratory muscle training improves exercise tolerance in recreational soccer players without concomitant gain in soccer-specific fitness. J Strength Cond Res. 2014;28(2):483–91. https://doi.org/10.1519/JSC.0b013e31829d24b0.
114. Gabbett TJ. Do skill-based conditioning games offer a specific training stimulus for junior elite volleyball players? J Strength Cond Res. 2008;22(2):509–17. https://doi.org/10.1519/JSC.0b013e3181634550.
115. Gabbett T, Georgieff B, Anderson S, Cotton B, Savovic D, Nicholson L. Changes in skill and physical fitness following training in talent-identified volleyball players. J Strength Cond Res. 2006;20(1):29–35. https://doi.org/10.1519/R-16814.1.
116. Duncan MJ, Woodfield L, Al-Nakeeb Y. Anthropometric and physiological characteristics of junior elite volleyball players. Br J Sports Med. 2006;40(7):649–51. https://doi.org/10.1136/bjsm.2005.021998.

117. Scott TJ, Duthie GM, Delaney JA, Sanctuary CE, Ballard DA, Hickmans JA, Dascombe BJ. The validity and contributing physiological factors to 30-15 intermittent fitness test performance in rugby league. J Strength Cond Res. 2017;31(9):2409–16. https://doi.org/10.1519/jsc.0000000000001702.
118. Gabbett TJ, Wheeler AJ. Predictors of repeated high-intensity-effort ability in rugby league players. Int J Sports Physiol Perform. 2015;10(6):718–24. https://doi.org/10.1123/ijspp.2014-0127.
119. Gabbett TJ. Performance changes following a field conditioning program in junior and senior rugby league players. J Strength Cond Res. 2006;20(1):215–21. https://doi.org/10.1519/R-16554.1.
120. Till K, Cobley S, O'Hara J, Chapman C, Cooke C. A longitudinal evaluation of anthropometric and fitness characteristics in junior rugby league players considering playing position and selection level. J Sci Med Sport. 2013;16(5):438–43. https://doi.org/10.1016/j.jsams.2012.09.002.
121. Fargeas-Gluck MA, Leger LA. Comparison of two aerobic field tests in young tennis players. J Strength Cond Res. 2012;26(11):3036–42. https://doi.org/10.1519/JSC.0b013e3182472fc3.
122. Brechbuhl C, Girard O, Millet GP, Schmitt L. On the use of a test to exhaustion specific to tennis (TEST) with ball hitting by elite players. PLoS One. 2016;11(4):e0152389. https://doi.org/10.1371/journal.pone.0152389.
123. Ballester R, Huertas F, Molina E, Sanabria D. Sport participation and vigilance in children: influence of different sport expertise. J Sport Health Sci. 2018;7(4):497–504.
124. Smith J, DePhillipo N, Kimura I, Kocher M, Hetzler R. Prospective functional performance testing and relationship to lower extremity injury incidence in adolescent sports participants. Int J Sports Phys Ther. 2017;12(2):206.
125. Gabbett TJ, Georgieff B. The development of a standardized skill assessment for junior volleyball players. Int J Sports Physiol Perform. 2006;1(2):95–107.
126. Bianco A, Jemni M, Thomas E, Patti A, Paoli A, Roque J, Palma C, Tabacchi G. A systematic review to determine reliability and usefulness of the field-based test batteries for the assessment of physical fitness in adolescents - the ASSO project. Inj J Occup Med Environ Health. 2015;28(3):445–78.
127. Williford HN, Scharff-Olson M, Duey WJ, Pugh S, Barksdale JM. Physiological status and prediction of cardiovascular fitness in highly trained youth soccer athletes. J Strength Cond Res. 1999;13(1):10–5.
128. Gabbett TJ. A comparison of physiological and anthropometric characteristics among playing positions in junior rugby league players. Br J Sports Med. 2005;39(9):675–80.
129. Mayorga-Vega D, Aguilar-Soto P, Viciana J. Criterion-related validity of the 20-m shuttle run test for estimating cardiorespiratory fitness: a meta-analysis. J Sports Sci Med. 2015;14:536–47.
130. Castagna C, Impellizzeri FM, Chamari K, Carlomagno D, Rampinini E. Aerobic fitness and yo-yo continuous and intermittent tests performances in soccer players: a correlation study. J Strength Cond Res. 2006;20(2):320–5. https://doi.org/10.1519/R-18065.1.
131. Hermassi S, Ingebrigtsen J, Schwesig R, Fieseler G, Delank K-S, Chamari K, Shephard RJ, Chelly M-S. Effects of in-season short-term aerobic and high-intensity interval training program on repeated sprint ability and jump performance in handball players. J Sports Med Phys Fitness. 2018;58(1-2):50–6.
132. Owen C, Jones P, Comfort P. The reliability of the submaximal version of the Yo-Yo intermittent recovery test in elite youth soccer. J Trainol. 2017;6(1):31–4.
133. Castagna C, Impellizzeri FM, Rampinini E, D'Ottavio S, Manzi V. The Yo-Yo intermittent recovery test in basketball players. J Sci Med Sport. 2008;11(2):202–8. https://doi.org/10.1016/j.jsams.2007.02.013.
134. Klusemann MJ, Pyne DB, Fay TS, Drinkwater EJ. Online video-based resistance training improves the physical capacity of junior basketball athletes. J Strength Cond Res. 2012;26(10):2677–84. https://doi.org/10.1519/JSC.0b013e318241b021.
135. Lockie RG, Jalilvand F, Moreno MR, Orjalo AJ, Risso FG, Nimphius S. Yo-Yo intermittent recovery test level 2 and its relationship with other typical soccer field tests in female collegiate soccer players. J Strength Cond Res. 2017;31(10):2667–77. https://doi.org/10.1519/JSC.0000000000001734.
136. Bradley PS, Bendiksen M, Dellal A, Mohr M, Wilkie A, Datson N, Orntoft C, Zebis M, Gomez-Diaz A, Bangsbo J, Krustrup P. The application of the Yo-Yo intermittent endurance level 2 test to elite female soccer populations. Scand J Med Sci Sports. 2014;24(1):43–54. https://doi.org/10.1111/j.1600-0838.2012.01483.x.
137. Rampinini E, Sassi A, Azzalin A, Castagna C, Menaspa P, Carlomagno D, Impellizzeri FM. Physiological determinants of Yo-Yo intermittent recovery tests in male soccer players. Eur J Appl Physiol. 2010;108(2):401–9. https://doi.org/10.1007/s00421-009-1221-4.
138. Fanchini M, Schena F, Castagna C, Petruolo A, Combi F, McCall A, Impellizzeri M. External responsiveness of the Yo-Yo IR test level 1 in high-level male soccer players. Int J Sports Med. 2015;36(9):735–41. https://doi.org/10.1055/s-0035-1547223.
139. Nicks CR, Morgan DW, Fuller DK, Caputo JL. The influence of respiratory muscle training upon intermittent exercise performance. Int J Sports Med. 2009;30(1):16–21. https://doi.org/10.1055/s-2008-1038794.
140. Flatt AA, Esco MR. Evaluating individual training adaptation with smartphone-derived heart rate variability in a Collegiate Female Soccer Team. J Strength Cond Res. 2016;30(2):378–85. https://doi.org/10.1519/JSC.0000000000001095.

141. Dupont G, Defontaine M, Bosquet L, Blondel N, Moalla W, Berthoin S. Yo-Yo intermittent recovery test versus the Universite de Montreal Track Test: relation with a high-intensity intermittent exercise. J Sci Med Sport. 2010;13(1):146–50. https://doi.org/10.1016/j.jsams.2008.10.007.
142. Lockie RG, Moreno MR, Orjalo AJ, Stage AA, Liu TM, Birmingham-Babauta SA, Hurley JM, Torne IA, Beiley MD, Risso FG. Repeated-sprint ability in division I collegiate male soccer players: positional differences and relationships with performance tests. J Strength Cond Res. 2017;33(5):1362–70.
143. Makhlouf I, Castagna C, Manzi V, Laurencelle L, Behm DG, Chaouachi A. Effect of sequencing strength and endurance training in young male soccer players. J Strength Cond Res. 2016;30(3):841–50. https://doi.org/10.1519/JSC.0000000000001164.
144. Moss SL, McWhannell N, Michalsik LB, Twist C. Anthropometric and physical performance characteristics of top-elite, elite and non-elite youth female team handball players. J Sports Sci. 2015;33(17):1780–9. https://doi.org/10.1080/02640414.2015.1012099.
145. Souhail H, Castagna C, Mohamed HY, Younes H, Chamari K. Direct validity of the yo-yo intermittent recovery test in young team handball players. J Strength Cond Res. 2010;24(2):465–70. https://doi.org/10.1519/JSC.0b013e3181c06827.
146. Purkhus E, Krustrup P, Mohr M. High-intensity training improves exercise performance in elite women volleyball players during a competitive season. J Strength Cond Res. 2016;30(11):3066–72. https://doi.org/10.1519/JSC.0000000000001408.
147. Vescovi JD. Locomotor, heart-rate, and metabolic power characteristics of youth women's field hockey: female athletes in motion (FAiM) study. Res Q Exerc Sport. 2016;87(1):68–77. https://doi.org/10.1080/02701367.2015.1124972.
148. Serpiello FR, McKenna MJ, Stepto NK, Bishop DJ, Aughey RJ. Performance and physiological responses to repeated-sprint exercise: a novel multiple-set approach. Eur J Appl Physiol. 2011;111(4):669–78. https://doi.org/10.1007/s00421-010-1687-0.
149. Castagna C, Impellizzeri F, Cecchini E, Rampinini E, Alvarez JC. Effects of intermittent-endurance fitness on match performance in young male soccer players. J Strength Cond Res. 2009;23(7):1954–9. https://doi.org/10.1519/JSC.0b013e3181b7f743.
150. Chaouachi A, Manzi V, Wong del P, Chaalali A, Laurencelle L, Chamari K, Castagna C. Intermittent endurance and repeated sprint ability in soccer players. J Strength Cond Res. 2010;24(10):2663–9. https://doi.org/10.1519/JSC.0b013e3181e347f4.
151. Thomas A, Dawson B, Goodman C. The yo-yo test: reliability and association with a 20-m shuttle run and VO(2max). Int J Sports Physiol Perform. 2006;1(2):137–49.
152. Veale JP, Pearce AJ, Carlson JS. The Yo-Yo intermittent recovery test (Level 1) to discriminate elite junior Australian football players. J Sci Med Sport. 2010;13(3):329–31. https://doi.org/10.1016/j.jsams.2009.03.006.

21 Muscle Strength and Dynamic Balance Stability Tests

Frank R. Noyes and Sue Barber-Westin

21.1 Introduction

The objective measurement of an athlete's strength and dynamic balance (or postural control) is essential throughout the rehabilitation period after anterior cruciate ligament (ACL) reconstruction and other major knee operations. After major knee surgery, we use objective muscle strength and dynamic balance tests to advance patients through the initial phases of rehabilitation and before return to running and agility training, plyometric and advanced neuromuscular training, and final release to full sports activities. Manual muscle tests and gait analysis are performed early postoperatively and eventually, isometric, isokinetic, and dynamic balance tests are used according to the activities the patient desires to resume. There are other neuromuscular tests and assessments we conduct prior to the initiation of training and eventual return to sport (RTS), which are detailed in Chap. 20.

In 2011, we performed a systematic review that analyzed the factors investigators had used over the previous 10 years to determine when return to unrestricted athletics after ACL reconstruction was allowed [1]. Of 264 studies in the review, 105 (40%) failed to provide any RTS criteria. Only 35 studies (13%) noted the objective criteria required for RTS. Muscle strength was required in 25 studies (9%) and single-leg hop testing was noted in 10 studies (4%). More recently, many investigators have recommended the use of muscle strength and dynamic balance testing prior to RTS [2–10]. Abrams et al. [11] performed a systematic review of 88 studies to determine normative data for function tests used after ACL reconstruction for RTS. The most commonly reported functional tests were single-leg hop tests (single-leg hop, cross-over hop, triple hop, 6-m timed hop) and the most commonly reported muscle strength test was the isokinetic evaluation of the peak torque of knee flexors and extensors. This chapter reviews common tests used to measure lower extremity muscle strength and dynamic balance stability, based on equipment available to the clinician. Advantages, disadvantages, and normative data are provided to assist the clinician in the selection and interpretation of test results.

21.2 Muscle Strength Tests

21.2.1 Isokinetic Testing

Isokinetic testing (Fig. 21.1) uses a selected fixed angular velocity with resistance and is typically

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_21

Fig. 21.1 Isokinetic testing (From Heckmann et al. [12])

performed at slow, medium, and fast angular velocities (60°/s, 180°/s, 300°/s). Davies et al. [13] recently summarized the advantages and limitations of isokinetic testing (Table 21.1). Although muscle strength is commonly evaluated in the clinic with a hand-held dynamometer (HHD) using isometric resistance, isokinetic testing is preferred because it involves dynamic muscle performance. Adequate reliability of isokinetic testing has been reported in multiple investigations [14–18].

Correlations between muscle strength measured isokinetically and functional movements have been reported in multiple studies [19–22]. For instance, Rouis et al. [22] reported a significant relationship between vertical jump height and knee extensor peak torque at 240°/s ($R = 0.88$, $P < 0.001$), as did Loturco et al. [20] at 300°/s ($R = 0.66$, $P < 0.05$). Silwowski et al. [23] reported correlations between knee extensor peak torque at 60°/s and vertical jump height ($R = 0.49$, $P = 0.005$), squat jump height ($R = 0.48$, $P = 0.007$), and 30-s jump test height ($R = 0.52$, $P = 0.003$). Ithurburn et al. [19] reported a significant relationship between isokinetic quadriceps strength side-to-side symmetry and mechanics during a single-leg drop landing task (i.e., knee flexion excursion, peak trunk flexion, peak extension moment [$P < 0.001$]).

Table 21.1 Advantages and limitations of isokinetic testing[a]

Advantages
• Provides reliable objective documentation of dynamic muscle performance
• Efficient: loads a dynamically contracting muscle to its maximum capability at all points throughout the range of motion
• Because of the accommodating resistance, a muscle can be challenged to its maximal capacity through an entire range of motion (physiologic Blix curve)
• Muscle groups can be isolated for testing and rehabilitation
• Inherently safe for pain and fatigue
• Validity based on correlations with other functional tests
• Concentric isokinetic exercises produce minimal post-exercise delayed onset muscle soreness
• Exercise at different angular velocities through a velocity spectrum
• Because of specificity of training, exercising at the faster angular velocities at higher intensities can recruit fast twitch muscle fibers which are critically important in functional activities. There is the potential to increase muscle power, quickness of muscle force development, time rate of torque development, torque acceleration energy and rate of force development; all important for athletic performance
• The reciprocal innervation time of agonist and antagonist muscle contractions can be decreased by having the patient work at faster angular velocities and try to recruit the agonist/antagonist as quickly as possible
• Joint compressive forces decrease with higher angular velocities (fluid film lubrication model)
• The faster the movement of a surface (articular cartilage) over a fluid medium (synovial fluid), the lower the surface pressure (Bernoulli's principle)
• There is a 30°/s physiologic (strengthening) overflow to slower angular velocities with isokinetic resistance
• There is a 30–40° range of motion strengthening overflow during the performance of short-arc exercises
• Computerized feedback allows improvement in torque control accuracy
• Real-time feedback is available to the patient for motivation during exercise
• Short-arc testing and/or using a proximally placed pad can decrease anterior tibial translation
Limitations
• Isolated muscle group testing and rehabilitation
• Nonfunctional patterns of movements
• Limited velocities to actually replicate the actual speeds of sports performance

(continued)

Table 21.1 (continued)

• Increased joint compressive forces at slower speeds
• May cause increased anterior tibial translation with testing or rehabilitation if using the full range of motion

[a]From Davies et al. [13]

Undheim et al. [24] conducted a systematic review of 39 studies to determine the most common variables reported from isokinetic testing after ACL reconstruction. Peak torque of the knee extensors and flexors was the most commonly reported outcome measurement, found in 82% of the studies. Results of testing were usually reported as a limb symmetry index (LSI) and/or as a unilateral ratio (hamstrings:quadriceps [H:Q] ratio). The most common test angular velocities were 60°/s and 180°/s. Only 8 studies (20%) reported strength LSI as a component of their RTS criteria.

After ACL reconstruction, we usually begin isokinetic testing in athletes after postoperative week 12 assuming no contraindications exist (see Chap. 11). We test in an isometric mode initially (at week 12) and then advance to test at 180°/s and 300°/s approximately 1 month later [12]. Tests are performed in athletes until <10% deficits are achieved in bilateral comparisons of quadriceps and hamstrings peak torque. The H:Q ratio is also monitored, with the goal of achieving 70–75% at 180°/s and 75–80% at 300°/s prior to RTS. Our isokinetic test protocol is shown below.

(1) Make sure no test contraindications are present such as knee joint pain, swelling, limited knee range of motion, or patellar instability.
(2) Have the patient warm-up for 5 min on a stationary bicycle.
(3) Ensure the equipment is properly calibrated. Properly position and stabilize the patient on the test equipment.
(4) Educate the patient regarding the requirements of the test.
(5) Test the noninvolved extremity first.
(6) Use verbal encouragement throughout the test such as “push and pull as hard and fast as possible.”
(7) Use standard test protocols for each test velocity. There are many protocols described elsewhere for strength, power, and endurance [25]. In our clinic, patients perform 5 repetitions at 180°/s and 15 repetitions at 300°/s.

Several investigations have published normative data of isokinetic strength data for athletes [26–32]. Samples for 1 angular velocity (60°/s) according to sport and gender are shown in Table 21.2. We previously published normative isokinetic strength data in 1140 athletes 9–17 years of age; mean peak torque (300°/s) data normalized for body weight according to age and gender is shown in Table 21.3 [33].

21.2.2 Isometric Testing Using an Isokinetic Dynamometer

Isometric testing of muscle strength on an isokinetic dynamometer is a valuable option for patients who have contraindications to isokinetic test protocols. We use this strength measurement early after surgery to protect healing ligament grafts or in cases of patellofemoral pain. For instance, 12 weeks after ACL reconstruction, patients must demonstrate no more than a 30% deficit in isometric knee extensor and flexor strength from the opposite side in order to advance to the next phase of rehabilitation (see Chap. 11).

Burland et al. [34] determined that high isometric knee extension strength (Humac isokinetic dynamometer, 60° of knee flexion, average peak torque of 3 trials) measured 6 months after ACL reconstruction correlated with RTS in a group of 50 adolescent patients ($R^2 = 0.52$, $P = 0.002$). Patients who RTS had a significantly greater LSI for isometric extension strength compared with those who did not return (93% and 69%, respectively, $P = 0.001$). Herrington et al. [35] reported significant differences in knee extensor isometric peak force (Biodex, 90° knee flexion, highest torque from 5 repetitions) between the ACL-reconstructed knee and contralateral limb in 15 professional soccer players tested a mean of 8 months postop-

Table 21.2 Mean isokinetic lower extremity normative data at 60°/s in athletes

Study	Cohort			Extension peak torque (Nm)		Normalized extension peak torque (Nm kg^{-1})		Flexion peak torque (Nm)		Normalized flexion peak torque (Nm kg^{-1})		H:Q ratio (Nm)	
	No. M/F	Mean age	Sport	Dom	Nondom	Dom	Nondom	Dom	Nondom	Dom	Nondom	Dom	Nondom
Risberg et al. [31]	143 F	21	Handball	166	166	2.4	2.4	95	93	1.4	1.4	58	57
Andrade et al. [26]	21 F	26	Handball	168	NP	2.3	NP	94	NP	1.3	NP	56	NP
Risberg et al. [31]	196 F	21	Soccer	148	146	2.3	2.3	88	85	1.4	1.3	60	5
Andrade et al. [26]	17 F	25	Soccer	169	NP	2.8	NP	91	NP	1.5	NP	54	NP
Rosene et al. [32]	10 F	19	Soccer	NP	NP	NP	NP	NP	NP	NP	NP	52	47
Rosene et al. [32]	10 F	19	Basketball	NP	NP	NP	NP	NP	NP	NP	NP	55	51
Buchanen et al. [27]	10 F	12–13	Basketball	96	92	1.7	1.7	45	42	0.8	0.7	45	44
Buchanen et al. [27]	9 F	26–33	Basketball	127	123	1.8	1.8	74	66	1.1	1.0	58	55
Kabacinski et al. [29]	14 F	20	Basketball	NP	NP	NP	NP	NP	NP	NP	NP	48	NP
Kabacinski et al. [29]	12 F	22	Volleyball	NP	NP	NP	NP	NP	NP	NP	NP	56	NP
Rosene et al. [32]	12 F	19	Volleyball	NP	NP	NP	NP	NP	NP	NP	NP	51	52
Rosene et al. [32]	23 F	19	Softball	NP	NP	NP	NP	NP	NP	NP	NP	47	47
Buchanen et al. [27]	11 M	12–13	Basketball	110	104	2.0	1.9	56	51	1.0	0.9	52	50
Buchanen et al. [27]	7 M	16–22	Basketball	187	191	2.3	2.4	120	115	1.5	1.4	64	61
Rosene et al. [32]	17 M	19	Soccer	NP	NP	NP	NP	NP	NP	NP	NP	50	50
Cheung et al. [28]	23 M	22	Soccer	NP	NP	3.0	2.9	NP	NP	1.9	1.7	63	58

Cheung et al. [28]	12 M	22	Volleyball	NP	NP	3.2	2.9	NP	NP	1.7	1.6	57	64
Rosene et al. [32]	9 M	19	Volleyball	NP	NP	NP	NP	NP	NP	NP	NP	51	47
O'Malley et al. [30]	44 M	24	Field athletes	NP	NP	2.6	2.5	NP	NP	1.6	1.6	NP	NP

F female, *M* male, *H:Q* hamstrings:quadriceps

Table 21.3 Mean normalized isokinetic lower extremity normative data (dominant leg) at 300°/s in athletes[a]

Age	No. M/F	Extension peak torque (Nm kg)	Flexion peak torque (Nm kg)	H:Q ratio (Nm kg)
9	10 F	98	75	82
10	22 F	106	82	
11	47 F	117	89	
12	76 F	117	89	
13	107 F	122	84	
14	206 F	122	85	
15	175 F	126	88	
16	141 F	126	89	
17	68 F	131	91	70
9	10 M	91	81	87
10	16 M	99	84	
11	9 M	106	97	
12	16 M	110	92	
13	17 M	126	92	
14	16 M	147	104	72
15	37 M	157	112	
16-17	56 M	160	107	
17	27 M	153	108	72

[a]From Barber-Westin et al. [33]

eratively (2.9 ± 0.2 Nm kg^{-1} and 3.7 ± 0.4 Nm kg^{-1}, respectively, $P = 0.0001$). The mean LSI was 81%; however, only 13% scored >90%. Norte et al. [36] reported significant differences in knee extensor isometric strength (Biodex, 90° knee flexion, 3 repetitions) between ACL-reconstructed knees and contralateral limbs in 34 patients tested a mean of 9 months postoperatively (1.9 ± 0.6 Nm/kg and 2.6 ± 0.7 Nm/kg, $P < 0.001$). Kuenze et al. [37] found, in ACL-reconstructed patients tested a mean of 31 months postoperatively, an association between isometric knee extensor strength and the number of landing errors on a drop-land task. The patients had a significant strength deficit (involved, 2.5 ± 0.8 Nm/kg, noninvolved 2.9 ± 0.6 Nm/kg, $P = 0.002$), whereas control participants did not (dominant, 2.9 ± 0.6 Nm/kg, nondominant, 2.8 ± 0.5 Nm/kg).

Adequate reliability of isometric testing of the knee extensors and flexors has been reported in many investigations [15, 18, 35, 38, 39]. Protocols for isometric testing on an isokinetic dynamometer typically involve the following:

(1) Make sure no test contraindications are present such as knee joint pain, swelling, limited knee range of motion, or patellar instability.
(2) Have the patient warm-up for 5 min on a stationary bicycle.
(3) Properly position the patient on the test equipment.
(4) Educate the patient regarding the requirements of the test.
(5) Test the noninvolved extremity first.
(6) Knee flexion angle set at 90° for quadriceps, 60° or 90° for hamstrings.
(7) Perform 3 maximal repetitions, average the 3 (or take the highest value for maximum torque).
(8) Convert to Nm and normalize to body weight.
(9) Use verbal encouragement throughout the test such as "push as hard as possible."

21.2.3 Isometric Testing with a Hand-Held Dynamometer

For clinicians who do not have access to isokinetic test equipment, isometric assessment of muscle strength with a HHD offers an objective measure preferable to manual muscle testing for RTS considerations. Reliability values of knee extensor and flexor have been reported to be high (interclass correlation coefficient [ICC], >0.90 [18, 40, 41]) to moderate [39]. For instance, Whiteley et al. [18] reported ICC for knee extensors and flexors of 0.91 and 0.96, respectively, with a HHD in 10 healthy males. Stark et al. [42] in a systematic review of 19 studies, noted a lack of standardization of patient placement, position of the tester, and the manner in which the force was applied. However, the studies in general showed HHD to have moderate-to-good reliability and validity when compared with isokinetic testing.

Hansen et al. [40] reported improved patient comfort when a portable fixed HHD was modified to be interfaced with the leg of a table. Compared with a standard configuration (with the dynamometer positioned on the patient's tibia), the modification resulted in greater quadriceps peak torque (209 ± 69 Nm and 248 ± 79 Nm, $P < 0.001$) and decreased pain on a visual analogue scale (3.1 ± 2.0 and 1.1 ± 1.3, respectively, $P = 0.01$). When comparing peak torque generated on an isokinetic dynamometer (243 ± 83 Nm), no significant difference existed with the modified position peak torque; however, there was a significant difference with the standard configuration ($P < 0.001$). Kim et al. [43] compared peak torque values and reliability of knee extensor measurements obtained from a HHD fixed with a belt and a non-fixed HHD (held in the examiner's hand) in 28 healthy female volunteers. These investigators reported significantly lower mean peak torque values from the non-fixed HHD method compared with the fixed HHD (right limb 47 ± 10 Nm and 59 ± 17 Nm, respectively, $P < 0.05$; left limb 53 ± 13 Nm and 58 ± 17 Nm, respectively, $P < 0.05$). There was no significant difference in peak torques measured between the fixed HHD and an isokinetic dynamometer. Both fixed HHD and non-fixed HHD methods were highly reliable, with ICCs all >0.90.

Whiteley et al. [18] reported medium to high correlations between concentric isometric and isokinetic peak torque values for the extensors ($R = 0.54–0.62$ at 60°/s, $R = 0.45–0.48$ at 300°/s) and the flexors ($R = 0.52–0.55$ at 60°/s and $R = 0.33–0.38$ at 300°/s). Reference values for 270 children and adolescents are available from Beenakker et al. [44]. Protocols for isometric testing using a HHD typically involve the following:

(1) Make sure no test contraindications are present such as knee joint pain, swelling, limited knee range of motion, or patellar instability.
(2) Have the patient warm-up for 5 min on a stationary bicycle.
(3) Properly position the patient. Use stabilizing straps to ensure an isometric contraction is measured.
(4) Educate the patient regarding the requirements of the test.
(5) Test the noninvolved extremity first.
(6) Knee extensors are typically tested with the patient seated, knee flexed to 90°, with the dynamometer placed on the anterior aspect of the shank, proximal to the ankle joint.
(7) Knee flexors are usually tested with the patient seated, knee flexion to 90°, with the dynamometer placed on the posterior aspect of the shank, proximal to the ankle joint.
(8) Perform 3 maximal repetitions, with 1 min rest between tests. Use either the average of the three repetitions or take the highest value.
(9) Convert to Nm and normalize to body weight
(10) Use verbal encouragement throughout the test such as "push as hard as possible."

21.2.4 1-Repetition Maximum Leg Press

If isokinetic or isometric equipment are not available, a 1-repetition maximum (1RM) leg press is recommended if weight room equipment, an experienced test administrator, and a sufficient amount of time to safely conduct the test are available [45, 46]. Adequate reliability of the 1RM test has been documented in several investigations [47–50]. Seo et al. [50] tested 30 healthy males and females aged 18–35 years twice, 7 days apart, to determine the reliability of several 1RM tests. Mean leg press 1RM loads on test sessions 1 and 2 were 102.0 ± 4.1 kg and 102.5 ± 4.0 kg (ICC 0.997; $P < 0.01$), respectively, for men and 60.9 ± 3.6 and 61.3 ± 3.6 (ICC 0.997; $P < 0.01$), respectively, for women. The protocol used by these authors involves:

(1) A 5-min warm-up on a stationary bicycle, followed by 1 min of rest.
(2) 8–10 repetitions of a light load, ~50% of predicted 1RM, followed by 1 min of rest.
(3) 1 load of ~80% of predicted 1RM through full ROM, followed by 1 min of rest. After each successful performance, the weight is increased until a failed attempt occurs. A 1-min rest period is given between each attempt.
(4) The 1RM will usually be attained within 5 attempts.

21.2.5 Anaerobic Power: Vertical Jump

The vertical jump test is one of the most widely used measures to assess anaerobic power. A variety of methods have been described to measure vertical jump height. One of the most common and cost-effective is the countermovement (with arm swing) vertical jump measured with the Vertec Jump Training System (Sports Imports, Columbus, OH). First, the athlete's standing reach is measured with the athlete standing with the heels touching the ground. Then, a countermovement maximum jump with arm swing is performed three times and the highest jump obtained recorded (Fig. 21.2). Reliability for the assessment of vertical jump height using the Vertec is excellent, with ICCs >0.90 [52, 53]. The results may be compared with published data according to sports and gender (Table 21.4).

21.2.6 Abdominal Strength and Endurance

Sit-up Tests [72, 73]
Sit-up tests may be used to assess muscular strength and endurance. With the athlete lying supine with the knees bent and foot flat on the floor (held in place by a partner) and arms folded across the chest, sit-ups are performed by raising up so that the elbows touch the knees and then lower back so the shoulders touch the floor. The test may either include the number of repetitions completed in 60 s or may be done until exhaustion (execution until failure). Investigations have demonstrated adequate reliability of sit-up tests in normal subjects of 0.84 (reliability coefficient) [74] and chronic pain populations of 0.77 (ICC, test-retest) and 1.0 (ICC, inter-rater) [75]. Both the U.S. Army Physical Fitness Test and Presidential Fitness Test quantify how many times an athlete can perform a sit-up in 1 min [76].

Fig. 21.2 Vertical jump test using the Vertec (From Barber-Westin and Noyes [51])

Abdominal Endurance Test [77]
Abdominal endurance may be measured by positioning the athlete on a mat or cushion on their back with their arms by their side while sitting on their hands. Upon command, both legs are lifted together approximately 15 cm off the ground and the athlete is instructed to maintain this position for as long as possible. The amount of time that the athlete is able to stay in this position (keeping both legs off of the ground) is recorded with a digital stopwatch.

21.2.7 Core Stability

Core stability may be assessed using measures to subjectively determine how long proper posture is maintained over time. These measures include the prone-plank (Fig. 21.3a), side-bridge (Fig. 21.3b), and flexor endurance tests (Fig. 21.3c). These tests, easy to conduct in the clinical setting, are done until the athlete is unable to hold the test position [78, 79]. In the prone-plank test, the athlete lies prone with their feet or legs secured to a table. The upper body is lifted off the table so that it is parallel to the floor. In the side-bridge test, the athlete supports themselves on their feet and one elbow, keeping the body in a straight line with the supporting elbow side facing down. In the flexor endurance test, the athlete sits with knees and hips flexed to 90° and the upper body positioned 60° from the bed.

Table 21.4 Sample results of countermovement vertical jump height according to sport and gender

Study	Sport, gender, age	Measurement method	Distance (cm)
Laffaye [54]	Collegiate and professional athletes	Force plate	
	Males		57.9 ± 7.0
	Females		42.6 + 6.3
Jones [55]	Collegiate athletes, female	Vertec	
	Pre-train		48.5 ± 6.3
	Post-train		49.8 ± 5.9
Vescovi [56]	Female athletes	Electronic timing mat	
	High school soccer, aged 15.1 ± 1.6 years		39.6 ± 4.7
	College soccer, aged 19.9 ± 0.9 years		40.9 ± 5.5
	College lacrosse, aged 19.7 ± 1.1 years		40.1 ± 5.6
Hoffman [57]	Lacrosse, elite, female, aged 19.2 ± 1.0 years	Vertec	
	Starters		38.4 ± 5.6
	Nonstarters		36.6 ± 6.1
Enemark-Miller [58]	Lacrosse, elite, female, aged 20.0 ± 1.4 years	Vertec	44.0 ± 6.2
Gabbett [59]	Basketball, male and female, aged 16.3 ± 0.7 years	Yardstick device	
	Warm-up open skills		50.9 ± 11.0
	Warm-up closed skills		50.8 ± 10.3
McCormick [60]	Basketball, high school females	Vertec	
	Frontal-plane plyometric pre-trained		48.26 ± 5.39
	Sagittal-plane plyometric pre-trained		47.72 ± 7.07
Roden [61]	Basketball, high school males	Electronic timing mat	
	High intensity. low repetition pre-trained		52.2 ± 6.3
	Medium intensity, high repetition pre-trained		53.1 ± 7.4
Mihalik [62]	Volleyball, club, male and female	Vertec	
	Complex trained, aged 20.3 ± 2.2 years		48.2 ± 8.6
	Compound trained, aged 20.9 ± 2.4 years		47.8 ± 8.0
Vaverka [63]	Volleyball, elite, male, aged 27.9 ± 7.1 years	Multi-camera system	
	No arm swing		37.9 ± 5.7
	With arm swing		52.2 ± 8.8
Noyes [64]	Volleyball, high school females, aged 15 ± 1 year	Vertec	40.1 ± 7.1
McFarland [65]	Soccer, collegiate	Electronic jump mat	
	Females		41.85 ± 4.98
	Males		58.47 ± 6.53
Harper [66]	Soccer, collegiate, males	NA	32.9 ± 6.1
De Hoyo [67]	Soccer, elite male, aged 18 ± 1 year	Infrared-ray cells built into OptoJump system	
	Back squat trained		40.0 ± 5.5
	Resisted sprint trained		37.0 ± 2.8
	Plyometric, speed, agility trained		37.9 ± 3.6
Hammami [68]	Soccer, elite male, aged 12–13 years	Ergojump system	
	Plyometric then balance trained		29.2 ± 2.9
	Balance then plyometric trained		26.8 ± 1.8
Noyes [69]	Soccer, high school females aged 15 ± 1 year	Vertec training system	32.9 ± 6.7
Steffen [70]	Soccer, high school females aged 16–18 years	Force platform	27.9 ± 3.2
Gabbett [71]	Rugby, elite, female, aged 18.9 ± 5.7 years	Yardstick device	
	Forwards		35.1 ± 8.0
	Backs		35.7 ± 5.9
	Hit-up forwards		34.3 ± 8.6
	Adjustables		35.6 ± 5.5
	Outside backs		37.0 ± 7.0

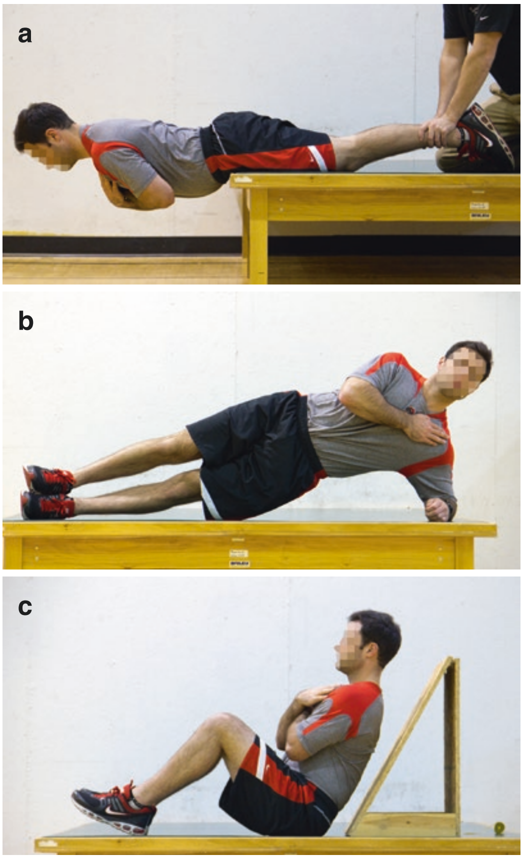


Fig. 21.3 Prone-plank (**a**), side-bridge (**b**), and flexor endurance (**c**) tests used to assess trunk endurance (From Chaudhari et al. [76])

21.3 Single-Leg Dynamic Balance Stability Tests

Dynamic stability requires the athlete to maintain balance while moving from a dynamic (i.e., deceleration from a sprint) to a static (i.e., stopping to change direction) state. This requires muscular control to maintain a stable center of gravity during sport-specific movements, especially those considered high-risk for noncontact ACL injuries such as pivoting and cutting. There are several single-leg dynamic stability tests that are cost-effective and feasible to perform in the clinic setting, including horizontal hops, the star excursion balance test (SEBT), the Y-balance test (YBT), the squat test, and the step-down test.

21.3.1 Hop Tests

Single-leg functional hop tests are one of the most commonly used measures of lower extremity power and dynamic balance [80–86]. These tests determine if abnormal LSI exists and subjectively assess an athlete's ability to hop and hold the landing on 1 leg [86]. They are reliable [83] and require only a tape measure which is secured to the ground. Our initial research demonstrated that a LSI of ≥85% was present in the majority (93%) of athletes [80]. We and many other investigators [2, 4, 9, 10, 87–90] now recommend a LSI of ≥90% for RTS. It is important to note that single-leg hop tests are a portion of the entire test battery that is recommended prior to RTS and should not be solely used to determine an athlete's muscle strength, control, or landing biomechanics [91–93].

If a video camera is available, it is recommended that the single-leg hop tests be recorded. On a subjective basis, one may observe if the player has the ability to "stick and hold" the landing with the knee and hips flexed, demonstrating adequate control of the core and upper extremity, as well as the lower extremity (Fig. 21.4a). Some players may be able to hold the landing, but their knee may wobble back and forth, along with poor upper body control and posture (Fig. 21.4b). In some instances, players will not be able to hold the landing at all and may even fall toward the ground (Fig. 21.4c). These players should be encouraged to practice single-leg balance exercises daily, along with single-leg strength training exercises several times a week to improve this problem.

21.3.1.1 Single Hop

A tape measure is secured to the ground for a distance of approximately 3 m. The athlete stands on the designated leg to be tested with their toe just behind the starting end of the tape. They are instructed to hop as far as possible forward and land on the same leg, holding that position for at least 2 s (Fig. 21.5a). The athlete is allowed to use their arms for balance as required. After a few

Fig. 21.4 Single-leg hop for distance video screening allows a qualitative assessment of an athlete's ability to control the upper and lower extremity upon landing, which may be rated as either good (**a**), fair to poor (**b**), or complete failure, fall to ground (**c**) (From Barber-Westin and Noyes [94])

Fig. 21.5 Single-leg hop tests. (**a**) Single hop. (**b**) Triple hop. (**c**) Triple cross-over hop (From Barber-Westin and Noyes [51])

trials, the athlete completes two single-leg hops on each limb. The distance hopped is recorded and the furthest distance achieved is used to calculate the LSI by dividing the distance hopped of the right leg by the distance hopped of the left leg, and multiplying the result by 100. This test has excellent reliability, with ICC >0.85 [95, 96]. Significant correlations have been reported between LSI scores and knee extensor peak torque tested isokinetically [8, 80, 97–99].

21.3.1.2 Triple Hop

A tape measure is secured to the ground for a distance of approximately 6 m. The athlete stands on the leg to be tested with their toe just behind the starting end of the tape. Three consecutive hops are done on the leg straight ahead (Fig. 21.5b). The athlete must be in control and hold the landing of the third hop for 3 s for the test to be valid. The athlete may use their arms for balance as required. After a few practice trials, two single-leg triple hops are done on each limb. The total distance hopped is measured, with the maximum distance for each leg recorded. The LSI is calculated by dividing the maximum distance hopped of the right leg by the maximum distance hopped of the left leg, and then multiplying the result by 100. Significant correlations have been noted between the distance hopped and isokinetic peak torque for the quadriceps and hamstrings at 60°/s and 180°/s [100]. The ICC of this test is excellent (>0.87 [96, 101]).

21.3.1.3 Triple Crossover Hop

A tape measure is secured to the ground for a distance of approximately 6 m. The athlete stands on the leg to be tested with their toe just behind the starting line. Three consecutive hops are done on that leg, crossing over the measuring tape on each hop (Fig. 21.5c). The athlete must be in control and hold the landing of the third hop for 3 s for the test to be valid. The athlete may use their arms for balance as required. After a few practice trials, two single-leg triple crossover hops are done on each limb. The total distance hopped is measured, and the LSI calculated as described above. This test has excellent reliability, with ICC >0.85 [96, 101]. Significant correlations have been reported between LSI and knee extensor peak torque tested isokinetically [98].

21.3.1.4 Timed 6-M Hop

A 6-m strip of marking tape is secured to the ground. The athlete stands on the leg to be tested with their toe just behind the starting line. They are instructed to hop forward on one leg as quickly as possible to the end of the line without losing their balance. The athlete may use their arms for balance as required. After a few trials, two single-leg timed hops are done on each limb. The time that the distance was hopped is recorded, and the LSI is calculated using the average time for each leg. This test has excellent reliability, with ICCs >0.90 [96, 101, 102]. Significant correlations have been reported between LSI and knee extensor peak torque tested isokinetically [98].

21.3.2 Star Excursion Balance Test

The SEBT has been used extensively to measure dynamic postural control in uninjured athletes [103–114], athletes who completed neuromuscular retraining [105, 115–117], patients with chronic ankle instability [118–121], patients with low back pain [122–124], and individuals with an ACL injury [125–128]. The task requires the subject to maintain a stable base by balancing on one leg while reaching out with the other leg to touch the ground as far as possible in various directions. The stance leg requires strength, neuromuscular control, and adequate range of motion at the hip, knee, and ankle joints [129]. This test has adequate reliability between sessions (ICC, 0.84–0.93 [109, 130, 131]) and under inter-tester (ICC, 0.81–0.93 [132, 133]) and intra-tester (ICC, 0.81–0.96 [105, 130, 131, 133] conditions [134–136]. The SEBT was found to be associated with multidirectional speed, with more difficult reaches (medial and posteromedial) correlating with 40-m sprint time, agility *t*-test time, and a change of direction and acceleration test time in recreational male field sport athletes [107]. In another study, moderate to large correlations were found between SEBT posterior, lateral, and posterolateral reach distances and change of direction cutting tests, which the investigators interpreted to indicate that greater dynamic balance resulted in faster agility times [111].

The test should be conducted on a firm hard surface, such as concrete or a gymnastics floor and the subject should be barefoot. A grid is made on the floor consisting of 8 lines extending at 45° angles from the center of the grid. The lines are designated as anterior, anterior-lateral, anterior-medial, medial, lateral, posterior, posterior-lateral, and posterior-medial (Fig. 21.6). The athlete places their hands on their hips and the most distal aspect of their great toe on the center of the grid. While maintaining a single-leg stance on 1 leg, the opposite leg extends as far as possible and touches the chosen line. The foot only touches lightly in order not to assist balance. The athlete then returns to bilateral stance. The point where the foot touches the line is marked and measured using a standard tape measure. In

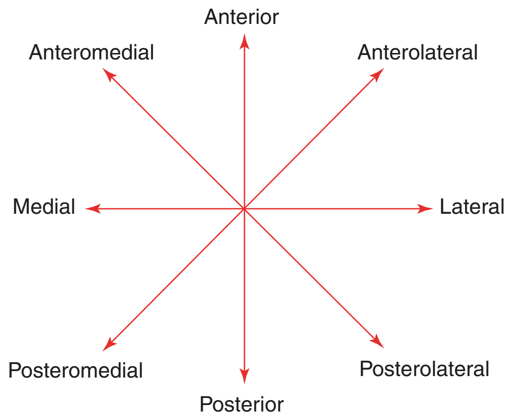


Fig. 21.6 Star excursion balance test. Directions are shown for a right limb stance (From Barber-Westin and Noyes [51])

order for the trial to be successful, the hands must remain on the athlete's hips at all times, the reach leg cannot provide support upon touch down, the heel of the stance leg must remain in its position in the center of the grid and not move or lift from the ground, and balance must be maintained. Four practice trials are conducted, followed by 3 test trials in each direction. A 1-min rest period is allowed between directions. Then, the same process is repeated on the opposite leg. The average of the 3 test trials is calculated for each leg in each direction.

The athlete's leg lengths are measured in the supine position from the anterior superior iliac spine to the distal tip of the medial malleolus using a standard tape measure. The leg length is used to normalize reach distances by dividing the distance reached by the leg length, then multiplying by 100 (Table 21.5) [137]. A change of 5–8% in normalized scores between independent test sessions is required to detect a clinically significant change according to published smallest detectable difference values [109, 136].

21.3.3 Y-Balance Test

Some investigators have simplified the SEBT to include only three reach directions (anterior, posteromedial, and posterolateral) [138–143], known as the YBT. In the SEBT, normalized

Table 21.5 Star excursion balance test normalized reach distances[a]

Study	Population	Anterior	Anteromedial	Posterior	Posteromedial	Posterolateral	Medial	Lateral
Steffen et al. [113]	1517 female elite soccer, handball players, uninjured leg		84 ± 6		95 ± 7		87 ± 7	
	55 female elite soccer, handball players ACL-injured leg		83 ± 7		94 ± 8		87 ± 7	
Steib et al. [117]	Female handball players, adult							
	20 controls	92 ± 7		107 ± 8			101 ± 8	83 ± 9
	21 trained neuromuscular program	94 ± 11		107 ± 9			101 ± 11	87 ± 11
Ambegaonkar et al. [134]	40 female collegiate athletes							
	Right side	69 ± 6			107 ± 10	106 ± 10		
	Left side	68 ± 6			112 ± 10	103 ± 10		
McLeod et al. [115]	Female high school basketball players							
	25 controls		87 ± 4	94 ± 5			90 ± 4	80 ± 7
	37 trained neuromuscular program		91 ± 7	105 ± 6			95 ± 6	86 ± 7
Alnahdi et al. [135]	Active collegiate students							
	31 women (mean rt-lt legs)	70 ± 4			93 ± 7	93 ± 8		
	30 men (mean rt-lt legs)	73 ± 7			106 ± 8	105 ± 10		
Van Lieshout et al. [136]	Adult athletes, 34 women, 21 men, data combined							
	Right leg	65 ± 5			78 ± 10	74 ± 12		
	Left leg	66 ± 5			80 ± 9	73 ± 11		
Munro et al. [109]	Active collegiate students, 11 women, 11 men, data combined for gender and legs	93	93	87	89	84	92	80

[a]Data normalized by % of leg length

reach distances are achieved through greater hip flexion, greater knee flexion, or a combination of the two. Robinson et al. [141] concluded that all 8 reach directions measured similar functional factors and that redundancy may occur, lending support to the YBT protocol. Lee et al. [140], in a group of 40 volunteer women, found positive correlations between all YBT reach directions and hip extensor and knee flexor isometric strength. Knee flexor strength correlated with performance in the anterior direction ($R = 0.71$, $P < 0.05$), posteromedial direction ($R = 0.71$, $P < 0.05$), and posterolateral direction ($R = 0.83$, $P < 0.05$). In a group of young male soccer players, Chtara et al. [138] reported significant relationships between knee extensor isometric strength and performance in anterior reach ($R = 0.45$, $P < 0.05$), posteromedial reach ($R = 0.47$, $P < 0.05$), and posterolateral reach ($R = 0.42$, $P < 0.05$).

A commercially available YBT Kit may be used to facilitate this test [144]. The kit consists of a stance platform to which three pieces of PVC pipe are attached in the anterior, posteromedial, and posterolateral reach directions. Each pipe is marked in 5-mm increments. The subject pushes a target along the pipe which standardizes the reach height. The target remains over the tape measure after the test, making the determination to reach distance precise. Subjects perform practice trials and then test trials as described for SEBT. Lower limb length is measured as previously described for normalization purposes. Plisky et al. [144] reported ICC values of 0.85–0.88 for the 3 reach directions in 15 male collegiate soccer players. Hudson et al. [145] reported normative values in 90 female collegiate volleyball players (Table 21.6). A composite score was obtained for each limb by adding the maximal reach distances in all directions, dividing the sum by 3 times the participant's limb length, and then multiplying that number by 100 to obtain a percentage. The composite scores were 94.1 ± 6.6% for the dominant limb and 93.9 ± 6.2% for the nondominant limb. Other investigations have also reported composite scores for athletes, shown in Table 21.6.

21.3.4 Squat Test

The single-leg squat test is a useful and reliable clinical tool that assesses frontal plane lower extremity motion. The goal is to identify weakness or poor control of the core and hip musculature with the observation of hip adduction and internal rotation, poor knee flexion, and knee abduction [152–155]. Studies have shown that females demonstrate increased ankle dorsiflexion, ankle pronation, hip adduction, hip flexion, hip external rotation, and decreased trunk lateral flexion compared with men [156]. Women also assume a greater overall valgus lower extremity alignment than men [156–158]. Correlations have been noted between control of frontal plane knee motion and hip muscle strength [154, 157–160] as well as knee flexor and extensor strength [158, 159]

The single-leg squat is conducted by asking the athlete to stand on 1 leg with their hands placed on their hips. The opposite leg should be maintained in approximately 45° of knee flexion during the entire test. The head and eyes should remain focused straight ahead. The athlete is instructed to squat down to 45° and return to single-leg stance without losing their balance (Fig. 21.7). We make this a more dynamic assessment by asking the athlete to perform 5 consecutive trials. The examiner notes the patient's overall trunk control and the position of the hip, knee, and foot throughout the test. The test result may be classified according to 5 categories that are rated as good, fair, or poor (Table 21.7) [154]. The rating may either be done during the test trial, or may be recorded in the frontal plane and conducted later when viewing the video. Acceptable interrater and intrarater reliability have been reported in several studies [152–155, 162].

21.3.5 Timed Step-Down Test

The timed step-down test represents a dynamic modification of the single-leg squat test [163, 164]. The subject stands on a 20-cm step with a

Table 21.6 Composite scores for the Y-balance test

Study	Cohort	No. subjects	Age	Gender	Composite score (%)
Hudson et al. [145]	Collegiate volleyball players	90	19.6 ± 1.2	Female	94.1 ± 6.6 (dominant) 93.9 ± 6.2 (nondominant)
Smith et al. [146]	Collegiate athletes	103	20.0 ± 1.4	NP	101.2 ± 7.1
Gorman et al. [147]	Single sport high school athletes	92	15.9 ± 1.2	Male and female	97.1 ± 8.2
	Multiple sport high school athletes	92	15.4 ± 1.2	Male and female	97.1 ± 8.4
Garrison et al. [148]	Baseball players	30	19.0 ± 1.1	Male	95.4 ± 6.4
Plisky et al. [130]	High school basketball players	105	NP	Female	98.4 ± 8.2
	High school basketball players	130	NP	Male	103.0 ± 8.0
Butler et al. [149]	Professional soccer players	44	26.2 ± 4.0	Male	101.8 ± 1.2
	Collegiate soccer players	37	18.8 ± 1.2	Male	100.9 ± 0.9
	High school soccer players	38	15.6 ± 1.0	Male	98.4 ± 1.1
Butler et al. [150]	American soccer players	26	16.1 ± 0.9	Male	97.8 ± 6.8
	Rwandan soccer players	26	16.5 ± 1.2	Male	105.6 ± 6.8
Chimera et al. [151]	Collegiate cross country	17	NP	Female	99 ± 5
	Collegiate cross country	13	NP	Male	101 ± 12
	Collegiate football players	60	NP	Male	102 ± 7
	Collegiate soccer players	28	NP	Female	102 ± 6
	Collegiate swimmers/divers	17	NP	Female	102 ± 7
	Collegiate athletes (all)	87	NP	Female	100 ± 6
	Collegiate athletes (all)	103	NP	Male	102 + 8

NP not provided

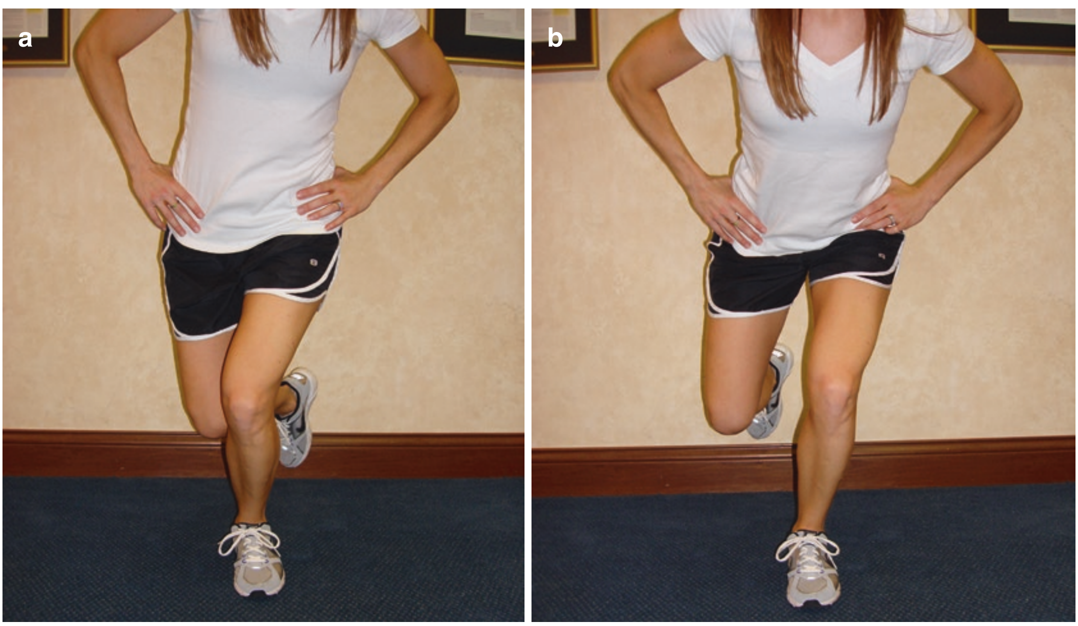


Fig. 21.7 Single-leg squat test. (**a**) Poor hip and knee control. (**b**) Good hip, trunk, and knee control (From Barber-Westin and Noyes [161])

Table 21.7 Clinical rating criteria for the single-leg squat test[a] [154]

Criteria	Criteria to be rated "good"
Overall impression of trial(s)	
Ability to maintain balance	Athlete does not lose balance
Perturbations of the athlete	Movement is performed smoothly
Depth of the squat	The squat is performed to at least 60° knee flexion
Speed of the squat	Squats performed at approximately 1 per 2 s
Trunk posture	
Trunk/thoracic lateral deviation or shift	No trunk/thoracic lateral deviation or shift
Trunk/thoracic rotation	No trunk/thoracic rotation
Trunk/thoracic lateral flexion	No trunk/thoracic lateral flexion
Trunk/thoracic forward flexion	No trunk/thoracic forward flexion
The pelvis "in space"	
Pelvic shunt or lateral deviation	No pelvic shunt or lateral deviation
Pelvic rotation	No pelvic rotation
Pelvic tilt	No pelvic tilt
Hip joint	
Hip adduction	No hip adduction
Hip (femoral) internal rotation	No hip (femoral) internal rotation
Knee joint	
Apparent knee valgus	No apparent knee valgus
Knee position relative to foot position	Center of knee remains over center of foot

[a]The athlete's performance is considered good if all of the requirements for at least 4 criteria are achieved. The performance is rated poor if they do not meet all of the requirements for at least 1 criterion

digital scale placed on the ground in front of the step [165]. The test limb is positioned with the knee fully extended and the toes even with the front edge of the step. A single-leg step-down consists of the subject flexing the test knee, touching the scale with the opposite heel with ≤10% of their body weight, and returning to the starting position. The subject performs as many repetitions as possible in 60 s. A step-down is not recorded if the heel does not touch the scale, if the subject places >10% body weight on the scale, or if the subject does not bring the foot up parallel with the step. In a study of 38 men and 33 women, the mean number of successful repetitions was 40 ± 13 and 37 ± 11, respectively. Moderate-to-strong correlations were found between performance on the test and hip strength and trunk endurance [163]. Kline et al. [164] reported that the results of this test conducted 3 months postoperatively in 30 ACL-reconstructed subjects significantly correlated with knee flexion angle excursion and knee extensor moment during treadmill running conducted 6 months postoperatively ($R = 0.65$, $P < 0.0001$ and $R = 0.54$, $P = 0.002$, respectively). The authors concluded that the test may be an early indicator of future problems with running and other sports-specific functional activities; however, future research is warranted for definitive conclusions.

References

1. Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. Arthroscopy. 2011;27(12):1697–705. https://doi.org/10.1016/j.arthro.2011.09.009.
2. Gokeler A, Welling W, Zaffagnini S, Seil R, Padua D. Development of a test battery to enhance safe return to sports after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2017;25(1):192–9. https://doi.org/10.1007/s00167-016-4246-3.
3. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med. 2016;50(13):804–8. https://doi.org/10.1136/bjsports-2016-096031.
4. Hamrin Senorski E, Svantesson E, Beischer S, Thomee C, Grassi A, Krupic F, Thomee R, Karlsson J, Samuelsson K. Concomitant injuries may not reduce the likelihood of achieving symmetrical muscle function one year after anterior cruciate ligament reconstruction: a prospective observational study based on 263 patients. Knee Surg Sports Traumatol Arthrosc. 2018;26(10):2966–77. https://doi.org/10.1007/s00167-018-4845-2.
5. Jang SH, Kim JG, Ha JK, Wang BG, Yang SJ. Functional performance tests as indicators of returning to sports after anterior cruciate ligament reconstruction. Knee. 2014;21(1):95–101. https://doi.org/10.1016/j.knee.2013.08.017.
6. Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. Br J Sports Med. 2016. https://doi.org/10.1136/bjsports-2015-095908.
7. Muller U, Kruger-Franke M, Schmidt M, Rosemeyer B. Predictive parameters for return to pre-injury

level of sport 6 months following anterior cruciate ligament reconstruction surgery. Knee Surg Sports Traumatol Arthrosc. 2015;23(12):3623–31. https://doi.org/10.1007/s00167-014-3261-5.
8. Palmieri-Smith RM, Lepley LK. Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. Am J Sports Med. 2015;43(7):1662–9. https://doi.org/10.1177/0363546515578252.
9. Toole AR, Ithurburn MP, Rauh MJ, Hewett TE, Paterno MV, Schmitt LC. Young athletes cleared for sports participation after anterior cruciate ligament reconstruction: how many actually meet recommended return-to-sport criterion cutoffs? J Orthop Sports Phys Ther. 2017;47(11):825–33. https://doi.org/10.2519/jospt.2017.7227.
10. Welling W, Benjaminse A, Seil R, Lemmink K, Zaffagnini S, Gokeler A. Low rates of patients meeting return to sport criteria 9 months after anterior cruciate ligament reconstruction: a prospective longitudinal study. Knee Surg Sports Traumatol Arthrosc. 2018;26(12):3636–44. https://doi.org/10.1007/s00167-018-4916-4.
11. Abrams GD, Harris JD, Gupta AK, McCormick FM, Bush-Joseph CA, Verma NN, Cole BJ, Bach BR Jr. Functional performance testing after anterior cruciate ligament reconstruction: a systematic review. Orthop J Sports Med. 2014;2(1):2325967113518305. https://doi.org/10.1177/2325967113518305.
12. Heckmann TP, Noyes FR, Barber-Westin S. Rehabilitation after ACL reconstruction. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete. 2nd ed. New York: Springer; 2018. p. 505–35. https://doi.org/10.1007/978-3-662-56558-2_22.
13. Davies GJ, Riemann B, Ellenbecker T. Role of isokinetic testing and training after ACL injury and reconstruction. In: Noyes FR, Barber-Westin S, editors. ACL injuries in the female athlete: causes, impacts, and conditioning programs. Berlin: Springer; 2018. p. 567–88. https://doi.org/10.1007/978-3-662-56558-2_24.
14. Carvalho HM, Coelho ESMJ, Ronque ER, Goncalves RS, Philippaerts RM, Malina RM. Assessment of reliability in isokinetic testing among adolescent basketball players. Medicina. 2011;47(8):446–52.
15. de Araujo Ribeiro Alvares JB, Rodrigues R, de Azevedo Franke R, da Silva BG, Pinto RS, Vaz MA, Baroni BM. Inter-machine reliability of the Biodex and Cybex isokinetic dynamometers for knee flexor/extensor isometric, concentric and eccentric tests. Phys Ther Sport. 2015;16(1):59–65. https://doi.org/10.1016/j.ptsp.2014.04.004.
16. Sole G, Hamren J, Milosavljevic S, Nicholson H, Sullivan SJ. Test-retest reliability of isokinetic knee extension and flexion. Arch Phys Med Rehabil. 2007;88(5):626–31. https://doi.org/10.1016/j.apmr.2007.02.006.
17. Tsiros MD, Grimshaw PN, Schield AJ, Buckley JD. Test-retest reliability of the biodex system 4 isokinetic dynamometer for knee strength assessment in paediatric populations. J Allied Health. 2011;40(3):115–9.
18. Whiteley R, Jacobsen P, Prior S, Skazalski C, Otten R, Johnson A. Correlation of isokinetic and novel hand-held dynamometry measures of knee flexion and extension strength testing. J Sci Med Sport. 2012;15(5):444–50. https://doi.org/10.1016/j.jsams.2012.01.003.
19. Ithurburn MP, Paterno MV, Ford KR, Hewett TE, Schmitt LC. Young athletes with quadriceps femoris strength asymmetry at return to sport after anterior cruciate ligament reconstruction demonstrate asymmetric single-leg drop-landing mechanics. Am J Sports Med. 2015;43(11):2727–37. https://doi.org/10.1177/0363546515602016.
20. Loturco I, Pereira LA, Kobal R, Abad CCC, Komatsu W, Cunha R, Arliani G, Ejnisman B, Pochini AC, Nakamura FY, Cohen M. Functional screening tests: interrelationships and ability to predict vertical jump performance. Int J Sports Med. 2018;39(3):189–97. https://doi.org/10.1055/s-0043-122738.
21. Newman MA, Tarpenning KM, Marino FE. Relationships between isokinetic knee strength, single-sprint performance, and repeated-sprint ability in football players. J Strength Cond Res. 2004;18(4):867–72. https://doi.org/10.1519/13843.1.
22. Rouis M, Coudrat L, Jaafar H, Filliard JR, Vandewalle H, Barthelemy Y, Driss T. Assessment of isokinetic knee strength in elite young female basketball players: correlation with vertical jump. J Sports Med Phys Fitness. 2015;55(12):1502–8.
23. Sliwowski R, Grygorowicz M, Wieczorek A, Jadczak L. The relationship between jumping performance, isokinetic strength and dynamic postural control in elite youth soccer players. J Sports Med Phys Fitness. 2018;58(9):1226–33. https://doi.org/10.23736/s0022-4707.17.07289-9.
24. Undheim MB, Cosgrave C, King E, Strike S, Marshall B, Falvey E, Franklyn-Miller A. Isokinetic muscle strength and readiness to return to sport following anterior cruciate ligament reconstruction: is there an association? A systematic review and a protocol recommendation. Br J Sports Med. 2015;49(20):1305–10. https://doi.org/10.1136/bjsports-2014-093962.
25. Davies GJ. A compendium of isokinetics in clinical usage. 4th ed. LaCrosse: S & S Publishers; 1994.
26. Andrade MDS, De Lira CAB, Koffes FDC, Mascarin NC, Benedito-Silva AA, Da Silva AC. Isokinetic hamstrings-to-quadriceps peak torque ratio: the influence of sport modality, gender, and angular velocity. J Sports Sci. 2012;30(6):547–53. https://doi.org/10.1080/02640414.2011.644249.
27. Buchanan PA, Vardaxis VG. Lower-extremity strength profiles and gender-based classification of basketball players ages 9-22 years. J Strength Cond

Res. 2009;23(2):406–19. https://doi.org/10.1519/JSC.0b013e3181942140.
28. Cheung RT, Smith AW, Wong del P. H:q ratios and bilateral leg strength in college field and court sports players. J Hum Kinet. 2012;33:63–71. https://doi.org/10.2478/v10078-012-0045-1.
29. Kabacinski J, Murawa M, Mackala K, Dworak LB. Knee strength ratios in competitive female athletes. PLoS One. 2018;13(1):e0191077. https://doi.org/10.1371/journal.pone.0191077.
30. O'Malley E, Richter C, King E, Strike S, Moran K, Franklyn-Miller A, Moran R. Countermovement jump and isokinetic dynamometry as measures of rehabilitation status after anterior cruciate ligament reconstruction. J Athl Train. 2018;53(7):687–95. https://doi.org/10.4085/1062-6050-480-16.
31. Risberg MA, Steffen K, Nilstad A, Myklebust G, Kristianslund E, Moltubakk MM, Krosshaug T. Normative quadriceps and hamstring muscle strength values for female, healthy, elite handball and football players. J Strength Cond Res. 2018;32(8):2314–23. https://doi.org/10.1519/jsc.0000000000002579.
32. Rosene JM, Fogarty TD, Mahaffey BL. Isokinetic hamstrings:quadriceps ratios in intercollegiate athletes. J Athl Train. 2001;36(4):378–83.
33. Barber-Westin SD, Noyes FR, Galloway M. Jump-land characteristics and muscle strength development in young athletes: a gender comparison of 1140 athletes 9 to 17 years of age. Am J Sports Med. 2006;34(3):375–84. https://doi.org/10.1177/0363546505281242.
34. Burland JP, Toonstra J, Werner JL, Mattacola CG, Howell DM, Howard JS. Decision to return to sport after anterior cruciate ligament reconstruction, part I: a qualitative investigation of psychosocial factors. J Athl Train. 2018;53(5):452–63. https://doi.org/10.4085/1062-6050-313-16.
35. Herrington L, Ghulam H, Comfort P. Quadriceps strength and functional performance after anterior cruciate ligament reconstruction in professional soccer players at time of return to sport. J Strength Cond Res. 2018. https://doi.org/10.1519/jsc.0000000000002749.
36. Norte GE, Hertel J, Saliba SA, Diduch DR, Hart JM. Quadriceps neuromuscular function in patients with anterior cruciate ligament reconstruction with or without knee osteoarthritis: a cross-sectional study. J Athl Train. 2018;53(5):475–85. https://doi.org/10.4085/1062-6050-102-17.
37. Kuenze CM, Foot N, Saliba SA, Hart JM. Drop-landing performance and knee-extension strength after anterior cruciate ligament reconstruction. J Athl Train. 2015;50(6):596–602. https://doi.org/10.4085/1062-6050-50.2.11.
38. Knezevic OM, Mirkov DM, Kadija M, Milovanovic D, Jaric S. Evaluation of isokinetic and isometric strength measures for monitoring muscle function recovery after anterior cruciate ligament reconstruction. J Strength Cond Res. 2014;28(6):1722–31. https://doi.org/10.1519/jsc.0000000000000307.
39. Toonstra J, Mattacola CG. Test-retest reliability and validity of isometric knee-flexion and -extension measurement using 3 methods of assessing muscle strength. J Sport Rehabil Tech Notes. 2013;7.
40. Hansen EM, McCartney CN, Sweeney RS, Palimenio MR, Grindstaff TL. Hand-held dynamometer positioning impacts discomfort during quadriceps strength testing: a validity and reliability study. Int J Sports Phys Ther. 2015;10(1):62–8.
41. Mentiplay BF, Perraton LG, Bower KJ, Adair B, Pua YH, Williams GP, McGaw R, Clark RA. Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: a reliability and validity study. PLoS One. 2015;10(10):e0140822. https://doi.org/10.1371/journal.pone.0140822.
42. Stark T, Walker B, Phillips JK, Fejer R, Beck R. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. PMR. 2011;3(5):472–9. https://doi.org/10.1016/j.pmrj.2010.10.025.
43. Kim WK, Kim DK, Seo KM, Kang SH. Reliability and validity of isometric knee extensor strength test with hand-held dynamometer depending on its fixation: a pilot study. Ann Rehabil Med. 2014;38(1):84–93. https://doi.org/10.5535/arm.2014.38.1.84.
44. Beenakker EA, van der Hoeven JH, Fock JM, Maurits NM. Reference values of maximum isometric muscle force obtained in 270 children aged 4–16 years by hand-held dynamometry. Neuromuscul Disord. 2001;11(5):441–6.
45. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, Newton RU, Triplett NT, Dziados JE. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. J Appl Physiol. 1995;78(3):976–89.
46. Reiman MP, Manske RC. Functional testing in human performance. Champaign: Human Kinetics; 2009.
47. Benton MJ, Raab S, Waggener GT. Effect of training status on reliability of one repetition maximum testing in women. J Strength Cond Res. 2013;27(7):1885–90. https://doi.org/10.1519/JSC.0b013e3182752d4a.
48. Neto JC, Cedin L, Dato CC, Bertucci DR, Perez S, Baldissera V. A single session of testing for one repetition maximum (1RM) with either exercises is trustworthy. J Exerc Physiol Online. 2015;18(3):74–80.
49. Redden J, Stokes K, Williams S. Establishing the reliability and limits of meaningful change of lower limb strength and power measures during seated leg press in elite soccer players. J Sports Sci Med. 2018;17(4):539–46.
50. Seo DI, Kim E, Fahs CA, Rossow L, Young K, Ferguson SL, Thiebaud R, Sherk VD, Loenneke JP, Kim D, Lee MK, Choi KH, Bemben DA, Bemben MG, So WY. Reliability of the one-repetition maxi-

mum test based on muscle group and gender. J Sports Sci Med. 2012;11(2):221–5.
51. Barber-Westin SD, Noyes FR. Testing for neuromuscular problems and athletic performance. In: ACL injuries in the female athlete. 2nd ed. New York: Springer; 2018. p. 289–333.
52. Chimera NJ, Swanik KA, Swanik CB, Straub SJ. Effects of plyometric training on muscle-activation strategies and performance in female athletes. J Athl Train. 2004;39(1):24–31.
53. Young W, MacDonald C, Heggen T, Fitzpatrick J. An evaluation of the specificity, validity and reliability of jumping tests. J Sports Med Phys Fitness. 1997;37(4):240–5.
54. Laffaye G, Wagner PP, Tombleson TI. Countermovement jump height: gender and sport-specific differences in the force-time variables. J Strength Cond Res. 2014;28(4):1096–105. https://doi.org/10.1519/JSC.0b013e3182a1db03.
55. Jones MT, Matthews TD, Murray M, Van Raalte J, Jensen BE. Psychological correlates of performance in female athletes during a 12-week off-season strength and conditioning program. J Strength Cond Res. 2010;24(3):619–28. https://doi.org/10.1519/JSC.0b013e3181cc23c3.
56. Vescovi JD, McGuigan MR. Relationships between sprinting, agility, and jump ability in female athletes. J Sports Sci. 2008;26(1):97–107. https://doi.org/10.1080/02640410701348644.
57. Hoffman JR, Ratamess NA, Neese KL, Ross RE, Kang J, Magrelli JF, Faigenbaum AD. Physical performance characteristics in National Collegiate Athletic Association Division III champion female lacrosse athletes. J Strength Cond Res. 2009;23(5):1524–9. https://doi.org/10.1519/JSC.0b013e3181b3391d.
58. Enemark-Miller EA, Seegmiller JG, Rana SR. Physiological profile of women's Lacrosse players. J Strength Cond Res. 2009;23(1):39–43. https://doi.org/10.1519/JSC.0b013e318185f07c.
59. Gabbett TJ, Sheppard JM, Pritchard-Peschek KR, Leveritt MD, Aldred MJ. Influence of closed skill and open skill warm-ups on the performance of speed, change of direction speed, vertical jump, and reactive agility in team sport athletes. J Strength Cond Res. 2008;22(5):1413–5. https://doi.org/10.1519/JSC.0b013e3181739ecd.
60. McCormick BT, Hannon JC, Newton M, Shultz B, Detling N, Young WB. The effects of frontal- and sagittal-plane plyometrics on change-of-direction speed and power in adolescent female basketball players. Int J Sports Physiol Perform. 2016;11(1):102–7. https://doi.org/10.1123/ijspp.2015-0058.
61. Roden D, Lambson R, DeBeliso M. The effects of a complex training protocol on vertical jump performance in male high school basketball players. J Sports Sci. 2014;2:21–6.
62. Mihalik JP, Libby JJ, Battaglini CL, McMurray RG. Comparing short-term complex and compound training programs on vertical jump height and power output. J Strength Cond Res. 2008;22(1):47–53. https://doi.org/10.1519/JSC.0b013e31815eee9e.
63. Vaverka F, Jandacka D, Zahradnik D, Uchytil J, Farana R, Supej M, Vodicar J. Effect of an arm swing on countermovement vertical jump performance in elite volleyball players: final. J Hum Kinet. 2016;53:41–50. https://doi.org/10.1515/hukin-2016-0009.
64. Noyes FR, Barber-Westin SD, Smith ST, Campbell T. A training program to improve neuromuscular indices in female high school volleyball players. J Strength Cond Res. 2011;25(8):2151–60. https://doi.org/10.1519/JSC.0b013e3181f906ef.
65. McFarland IT, Dawes JJ, Elder CL, Lockie RG. Relationship of two vertical jumping tests to sprint and change of direction speed among male and female collegiate soccer players. Sports. 2016;4(1). https://doi.org/10.3390/sports4010011.
66. Harper LD, Hunter R, Parker P, Goodall S, Thomas K, Howatson G, West DJ, Stevenson E, Russell M. Test-retest reliability of physiological and performance responses to 120 minutes of simulated soccer match play. J Strength Cond Res. 2016;30(11):3178–86. https://doi.org/10.1519/JSC.0000000000001400.
67. de Hoyo M, Gonzalo-Skok O, Sanudo B, Carrascal C, Plaza-Armas JR, Camacho-Candil F, Otero-Esquina C. Comparative effects of in-season full-back squat, resisted sprint training, and plyometric training on explosive performance in U-19 elite soccer players. J Strength Cond Res. 2016;30(2):368–77. https://doi.org/10.1519/JSC.0000000000001094.
68. Hammami R, Granacher U, Makhlouf I, Behm DG, Chaouachi A. Sequencing effects of balance and plyometric training on physical performance in youth soccer athletes. J Strength Cond Res. 2016;30(12):3278–89. https://doi.org/10.1519/JSC.0000000000001425.
69. Noyes FR, Barber-Westin SD, Tutalo Smith ST, Campbell T. A training program to improve neuromuscular and performance indices in female high school soccer players. J Strength Cond Res. 2013;27(2):340–51. https://doi.org/10.1519/JSC.0b013e31825423d9.
70. Steffen K, Bakka HM, Myklebust G, Bahr R. Performance aspects of an injury prevention program: a ten-week intervention in adolescent female football players. Scand J Med Sci Sports. 2008;18(5):596–604. https://doi.org/10.1111/j.1600-0838.2007.00708.x.
71. Gabbett TJ. Physiological and anthropometric characteristics of elite women rugby league players. J Strength Cond Res. 2007;21(3):875–81. https://doi.org/10.1519/R-20466.1.
72. Coen MM. 1985 National School Population Fitness Survey from President's Council on Physical Fitness and Sports. Washington, DC; 1986.
73. Bianco A, Lupo C, Alesi M, Spina S, Raccuglia M, Thomas E, Paoli A, Palma A. The sit up test to exhaustion as a test for muscular endurance evaluation. Springerplus. 2015;4:309. https://doi.org/10.1186/s40064-015-1023-6.
74. Alaranta H, Hurri H, Heliovaara M, Soukka A, Harju R. Non-dynamometric trunk performance tests: reli-

ability and normative data. Scand J Rehabil Med. 1994;26(4):211–5.
75. Harding VR, Williams AC, Richardson PH, Nicholas MK, Jackson JL, Richardson IH, Pither CE. The development of a battery of measures for assessing physical functioning of chronic pain patients. Pain. 1994;58(3):367–75.
76. Chaudhari AMW, Jamison ST, Best TM. Proximal risk factors for ACL injury: role of core stability. In: Noyes FR, Barber-Westin S, editors. ACL injuries in the female athlete: causes, impacts, and conditioning programs. Berlin: Springer; 2018. p. 189–205. https://doi.org/10.1007/978-3-662-56558-2_10.
77. Barber-Westin SD, Hermeto AA, Noyes FR. A six-week neuromuscular training program for competitive junior tennis players. J Strength Cond Res. 2010;24(9):2372–82. https://doi.org/10.1519/JSC.0b013e3181e8a47f.
78. McGill SM, Childs A, Liebenson C. Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. Arch Phys Med Rehabil. 1999;80(8):941–4.
79. Mills JD, Taunton JE, Mills WA. The effect of a 10-week training regimen on lumbo-pelvic stability and athletic performance in female athletes: a randomized-controlled trial. Phys Ther Sport. 2005;6(2):60–6. https://doi.org/10.1016/j.ptsp.2005.02.006.
80. Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. Clin Orthop Relat Res. 1990;255:204–14.
81. Engelen-van Melick N, van Cingel RE, Tijssen MP, Nijhuis-van der Sanden MW. Assessment of functional performance after anterior cruciate ligament reconstruction: a systematic review of measurement procedures. Knee Surg Sports Traumatol Arthrosc. 2013;21(4):869–79. https://doi.org/10.1007/s00167-012-2030-6.
82. Hegedus EJ, McDonough SM, Bleakley C, Baxter D, Cook CE. Clinician-friendly lower extremity physical performance tests in athletes: a systematic review of measurement properties and correlation with injury. Part 2-the tests for the hip, thigh, foot and ankle including the star excursion balance test. Br J Sports Med. 2015;49(10):649–56. https://doi.org/10.1136/bjsports-2014-094341.
83. Kroman SL, Roos EM, Bennell KL, Hinman RS, Dobson F. Measurement properties of performance-based outcome measures to assess physical function in young and middle-aged people known to be at high risk of hip and/or knee osteoarthritis: a systematic review. Osteoarthr Cartil. 2014;22(1):26–39. https://doi.org/10.1016/j.joca.2013.10.021.
84. Logerstedt D, Grindem H, Lynch A, Eitzen I, Engebretsen L, Risberg MA, Axe MJ, Snyder-Mackler L. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo ACL cohort study. Am J Sports Med. 2012;40(10):2348–56. https://doi.org/10.1177/0363546512457551.
85. Meierbachtol A, Rohman E, Paur E, Bottoms J, Tompkins M. Quantitative improvements in hop test scores after a 6-week neuromuscular training program. Sports Health. 2016;9(1):22–9. https://doi.org/10.1177/1941738116667933.
86. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med. 1991;19(5):513–8.
87. Hartigan EH, Axe MJ, Snyder-Mackler L. Time line for noncopers to pass return-to-sports criteria after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2010;40(3):141–54. https://doi.org/10.2519/jospt.2010.3168.
88. Herbst E, Hoser C, Hildebrandt C, Raschner C, Hepperger C, Pointner H, Fink C. Functional assessments for decision-making regarding return to sports following ACL reconstruction. Part II: clinical application of a new test battery. Knee Surg Sports Traumatol Arthrosc. 2015;23(5):1283–91. https://doi.org/10.1007/s00167-015-3546-3.
89. Logerstedt D, Di Stasi S, Grindem H, Lynch A, Eitzen I, Engebretsen L, Risberg MA, Axe MJ, Snyder-Mackler L. Self-reported knee function can identify athletes who fail return-to-activity criteria up to 1 year after anterior cruciate ligament reconstruction: a delaware-oslo ACL cohort study. J Orthop Sports Phys Ther. 2014;44(12):914–23. https://doi.org/10.2519/jospt.2014.4852.
90. Thomee R, Neeter C, Gustavsson A, Thomee P, Augustsson J, Eriksson B, Karlsson J. Variability in leg muscle power and hop performance after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2012;20(6):1143–51. https://doi.org/10.1007/s00167-012-1912-y.
91. Schelin L, Tengman E, Ryden P, Hager C. A statistically compiled test battery for feasible evaluation of knee function after rupture of the anterior cruciate ligament - derived from long-term follow-up data. PLoS One. 2017;12(5):e0176247. https://doi.org/10.1371/journal.pone.0176247.
92. Welling W, Benjaminse A, Seil R, Lemmink K, Gokeler A. Altered movement during single leg hop test after ACL reconstruction: implications to incorporate 2-D video movement analysis for hop tests. Knee Surg Sports Traumatol Arthrosc. 2018;26(10):3012–9. https://doi.org/10.1007/s00167-018-4893-7.
93. Wren TAL, Mueske NM, Brophy CH, Pace JL, Katzel MJ, Edison BR, Vandenberg CD, Zaslow TL. Hop distance symmetry does not indicate normal landing biomechanics in adolescent athletes with recent anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2018;48(8):622–9. https://doi.org/10.2519/jospt.2018.7817.
94. Barber-Westin SD, Noyes FR. Decreasing the risk of anterior cruciate ligament injuries in female athletes. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 373–404.
95. Gustavsson A, Neeter C, Thomee P, Silbernagel KG, Augustsson J, Thomee R, Karlsson J. A test

battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2006;14(8):778–88. https://doi.org/10.1007/s00167-006-0045-6.
96. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. Phys Ther. 2007;87(3):337–49.
97. Greenberger HB, Paterno MV. Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. J Orthop Sports Phys Ther. 1995;22(5):202–6.
98. Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. J Orthop Sports Phys Ther. 1994;20(2):60–73.
99. Xergia SA, Pappas E, Georgoulis AD. Association of the single-limb hop test with isokinetic, kinematic, and kinetic asymmetries in patients after anterior cruciate ligament reconstruction. Sports Health. 2014;7(3):217–23. https://doi.org/10.1177/1941738114529532.
100. Hamilton RT, Shultz SJ, Schmitz RJ, Perrin DH. Triple-hop distance as a valid predictor of lower limb strength and power. J Athl Train. 2008;43(2):144–51.
101. Ross MD, Langford B, Whelan PJ. Test-retest reliability of 4 single-leg horizontal hop tests. J Strength Cond Res. 2002;16(4):617–22.
102. Mansour JM, Pereira JM. Quantitative functional anatomy of the lower limb with application to human gait. J Biomech. 1987;20(1):51–8.
103. Bird SP, Markwick WJ. Musculoskeletal screening and functional testing: considerations for basketball athletes. Int J Sports Phys Ther. 2016;11(5):784–802.
104. Chimera NJ, Warren M. Use of clinical movement screening tests to predict injury in sport. World J Orthop. 2016;7(4):202–17. https://doi.org/10.5312/wjo.v7.i4.202.
105. Filipa A, Byrnes R, Paterno MV, Myer GD, Hewett TE. Neuromuscular training improves performance on the star excursion balance test in young female athletes. J Orthop Sports Phys Ther. 2010;40(9):551–8. https://doi.org/10.2519/jospt.2010.3325.
106. Hopper A, Haff EE, Barley OR, Joyce C, Lloyd RS, Haff GG. Neuromuscular training improves movement competency and physical performance measures in 11-13-year-old female netball athletes. J Strength Cond Res. 2017;31(5):1165–76. https://doi.org/10.1519/JSC.0000000000001794.
107. Lockie RG, Schultz AB, Callaghan SJ, Jeffriess MD. The relationship between dynamic stability and multidirectional speed. J Strength Cond Res. 2016;30(11):3033–43. https://doi.org/10.1519/JSC.0b013e3182a744b6.
108. McCann RS, Kosik KB, Terada M, Beard MQ, Buskirk GE, Gribble PA. Associations between functional and isolated performance measures in collegiate women's soccer players. J Sport Rehabil. 2016;26(5):376–85. https://doi.org/10.1123/jsr.2016-0016.
109. Munro AG, Herrington LC. Between-session reliability of the star excursion balance test. Phys Ther Sport. 2010;11(4):128–32. https://doi.org/10.1016/j.ptsp.2010.07.002.
110. Paz GA, Gabbett TJ, Maia MF, Santana H, Miranda H, Lima V. Physical performance and positional differences among young female volleyball players. J Sports Med Phys Fitness. 2016;57(10):1282–9.
111. Rouissi M, Haddad M, Bragazzi NL, Owen AL, Moalla W, Chtara M, Chamari K. Implication of dynamic balance in change of direction performance in young elite soccer players is angle dependent? J Sports Med Phys Fitness. 2018;58(4):442–9. https://doi.org/10.23736/s0022-4707.17.06752-4.
112. Sabin MJ, Ebersole KT, Martindale AR, Price JW, Broglio SP. Balance performance in male and female collegiate basketball athletes: influence of testing surface. J Strength Cond Res. 2010;24(8):2073–8. https://doi.org/10.1519/JSC.0b013e3181ddae13.
113. Steffen K, Nilstad A, Krosshaug T, Pasanen K, Killingmo A, Bahr R. No association between static and dynamic postural control and ACL injury risk among female elite handball and football players: a prospective study of 838 players. Br J Sports Med. 2017;51(4):253–9. https://doi.org/10.1136/bjsports-2016-097068.
114. Stiffler MR, Sanfilippo JL, Brooks MA, Heiderscheit BC. Star excursion balance test performance varies by sport in healthy division I collegiate athletes. J Orthop Sports Phys Ther. 2015;45(10):772–80. https://doi.org/10.2519/jospt.2015.5777.
115. McLeod TC, Armstrong T, Miller M, Sauers JL. Balance improvements in female high school basketball players after a 6-week neuromuscular-training program. J Sport Rehabil. 2009;18(4):465–81.
116. Pfile KR, Gribble PA, Buskirk GE, Meserth SM, Pietrosimone BG. Sustained improvements in dynamic balance and landing mechanics after a 6-week neuromuscular training program in college women's basketball players. J Sport Rehabil. 2016;25(3):233–40.
117. Steib S, Zahn P, Zu Eulenburg C, Pfeifer K, Zech A. Time-dependent postural control adaptations following a neuromuscular warm-up in female handball players: a randomized controlled trial. BMC Sports Sci Med Rehabil. 2016;8:33. https://doi.org/10.1186/s13102-016-0058-5.
118. Kalichman L, Lachman H, Freilich N. Long-term impact of ankle sprains on postural control and fascial densification. J Bodyw Mov Ther. 2016;20(4):914–9. https://doi.org/10.1016/j.jbmt.2016.04.002.
119. Kosik KB, Gribble PA. The effect of joint mobilization on dynamic postural control in patients with chronic ankle instability: a critically appraised topic. J Sport Rehabil. 2016:1–15. https://doi.org/10.1123/jsr.2016-0074.

120. Kwon YU, Blaise Williams DS. The effect of variable rest intervals and chronic ankle instability on triplanar ankle motion during performance of the Star Excursion Balance Test. Hum Mov Sci. 2017;52:143–50. https://doi.org/10.1016/j.humov.2017.01.013.
121. Wright CJ, Linens SW, Cain MS. A randomized controlled trial comparing rehabilitation efficacy in chronic ankle instability. J Sport Rehabil. 2016;26(4):238–49. https://doi.org/10.1123/jsr.2015-0189.
122. Hooper TL, James CR, Brismee JM, Rogers TJ, Gilbert KK, Browne KL, Sizer PS. Dynamic balance as measured by the Y-balance test is reduced in individuals with low back pain: a cross-sectional comparative study. Phys Ther Sport. 2016;22:29–34. https://doi.org/10.1016/j.ptsp.2016.04.006.
123. Ganesh GS, Chhabra D, Pattnaik M, Mohanty P, Patel R, Mrityunjay K. Effect of trunk muscles training using a star excursion balance test grid on strength, endurance and disability in persons with chronic low back pain. J Back Musculoskelet Rehabil. 2015;28(3):521–30. https://doi.org/10.3233/BMR-140551.
124. Tsigkanos C, Gaskell L, Smirniotou A, Tsigkanos G. Static and dynamic balance deficiencies in chronic low back pain. J Back Musculoskelet Rehabil. 2016;29(4):887–93. https://doi.org/10.3233/BMR-160721.
125. Dobija L, Coudeyre E, Pereira B. Measurement properties of the star excursion balance test in the anterior crucial ligament-deficient subjects - preliminary analysis. Ann Phys Rehabil Med. 2016;59S:e18. https://doi.org/10.1016/j.rehab.2016.07.043.
126. Harput G, Howard JS, Mattacola C. Comparison of muscle activation levels between healthy individuals and persons who have undergone anterior cruciate ligament reconstruction during different phases of weight-bearing exercises. J Orthop Sports Phys Ther. 2016;46(11):984–92. https://doi.org/10.2519/jospt.2016.5896.
127. Herrington L, Hatcher J, Hatcher A, McNicholas M. A comparison of star excursion balance test reach distances between ACL deficient patients and asymptomatic controls. Knee. 2009;16(2):149–52. https://doi.org/10.1016/j.knee.2008.10.004.
128. Zult T, Gokeler A, van Raay JJ, Brouwer RW, Zijdewind I, Hortobagyi T. An anterior cruciate ligament injury does not affect the neuromuscular function of the non-injured leg except for dynamic balance and voluntary quadriceps activation. Knee Surg Sports Traumatol Arthrosc. 2017;25(1):172–83. https://doi.org/10.1007/s00167-016-4335-3.
129. Olmsted LC, Carcia CR, Hertel J, Shultz SJ. Efficacy of the star excursion balance tests in detecting reach deficits in subjects with chronic ankle instability. J Athl Train. 2002;37(4):501–6.
130. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star excursion balance test as a predictor of lower extremity injury in high school basketball players. J Orthop Sports Phys Ther. 2006;36(12):911–9.
131. Kinzey SJ, Armstrong CW. The reliability of the star-excursion test in assessing dynamic balance. J Orthop Sports Phys Ther. 1998;27(5):356–60.
132. Gribble PA, Kelly SE, Refshauge KM, Hiller CE. Interrater reliability of the star excursion balance test. J Athl Train. 2013;48(5):621–6. https://doi.org/10.4085/1062-6050-48.3.03.
133. Hertel J, Miller SJ, Denegar CR. Intratester and intertester reliability during the star excurision balance tests. J Sport Rehabil. 2000;9:104–16.
134. Ambegaonkar JP, Mettinger LM, Caswell SV, Burtt A, Cortes N. Relationships between core endurance, hip strength, and balance in collegiate female athletes. Int J Sports Phys Ther. 2014;9(5):604–16.
135. Alnahdi AH, Alderaa AA, Aldali AZ, Alsobayel H. Reference values for the Y balance test and the lower extremity functional scale in young healthy adults. J Phys Ther Sci. 2015;27(12):3917–21. https://doi.org/10.1589/jpts.27.3917.
136. van Lieshout R, Reijneveld EA, van den Berg SM, Haerkens GM, Koenders NH, de Leeuw AJ, van Oorsouw RG, Paap D, Scheffer E, Weterings S, Stukstette MJ. Reproducibility of the modified star excursion balance test composite and specific reach direction scores. Int J Sports Phys Ther. 2016;11(3):356–65.
137. Gribble PA, Hertel J. Considerations for normalising measures of the star excursion balance test. Meas Phys Educ Exerc Sci. 2003;7(2):89–100.
138. Chtara M, Rouissi M, Bragazzi NL, Owen AL, Haddad M, Chamari K. Dynamic balance ability in young elite soccer players: implication of isometric strength. J Sports Med Phys Fitness. 2018;58(4):414–20. https://doi.org/10.23736/s0022-4707.16.06724-4.
139. Gribble PA, Hertel J, Denegar CR, Buckley WE. The effects of fatigue and chronic ankle instability on dynamic postural control. J Athl Train. 2004;39(4):321–9.
140. Lee DK, Kim GM, Ha SM, Oh JS. Correlation of the Y-balance test with lower-limb strength of adult women. J Phys Ther Sci. 2014;26(5):641–3. https://doi.org/10.1589/jpts.26.641.
141. Robinson R, Gribble P. Kinematic predictors of performance on the star excursion balance test. J Sport Rehabil. 2008;17(4):347–57.
142. Robinson RH, Gribble PA. Support for a reduction in the number of trials needed for the star excursion balance test. Arch Phys Med Rehabil. 2008;89(2):364–70. https://doi.org/10.1016/j.apmr.2007.08.139.
143. Walaszek R, Chwala W, Walaszek K, Burdacki M, Blaszczuk J. Evaluation of the accuracy of the postural stability measurement with the Y-balance test based on the levels of the biomechanical parameters. Acta Bioeng Biomech. 2017;19(2):121–8.
144. Plisky PJ, Gorman PP, Butler RJ, Kiesel KB, Underwood FB, Elkins B. The reliability of an instrumented device for measuring components of

the star excursion balance test. N Am J Sports Phys Ther. 2009;4(2):92–9.
145. Hudson C, Garrison JC, Pollard K. Y-balance normative data for female collegiate volleyball players. Phys Ther Sport. 2016;22:61–5. https://doi.org/10.1016/j.ptsp.2016.05.009.
146. Smith CA, Chimera NJ, Warren M. Association of Y balance test reach asymmetry and injury in division I athletes. Med Sci Sports Exerc. 2015;47(1):136–41. https://doi.org/10.1249/MSS.0000000000000380.
147. Gorman PP, Butler RJ, Rauh MJ, Kiesel K, Plisky PJ. Differences in dynamic balance scores in one sport versus multiple sport high school athletes. Int J Sports Phys Ther. 2012;7(2):148–53.
148. Garrison JC, Arnold A, Macko MJ, Conway JE. Baseball players diagnosed with ulnar collateral ligament tears demonstrate decreased balance compared to healthy controls. J Orthop Sports Phys Ther. 2013;43(10):752–8. https://doi.org/10.2519/jospt.2013.4680.
149. Butler RJ, Southers C, Gorman PP, Kiesel KB, Plisky PJ. Differences in soccer players' dynamic balance across levels of competition. J Athl Train. 2012;47(6):616–20. https://doi.org/10.4085/1062-6050-47.5.14.
150. Butler RJ, Queen RM, Beckman B, Kiesel KB, Plisky PJ. Comparison of dynamic balance in adolescent male soccer players from rwanda and the United States. Int J Sports Phys Ther. 2013;8(6):749–55.
151. Chimera NJ, Smith CA, Warren M. Injury history, sex, and performance on the functional movement screen and Y balance test. J Athl Train. 2015;50(5):475–85. https://doi.org/10.4085/1062-6050-49.6.02.
152. Ageberg E, Bennell KL, Hunt MA, Simic M, Roos EM, Creaby MW. Validity and interrater reliability of medio-lateral knee motion observed during a single-limb mini squat. BMC Musculoskelet Disord. 2010;11:265. https://doi.org/10.1186/1471-2474-11-265.
153. Alenezi F, Herrington L, Jones P, Jones R. The reliability of biomechanical variables collected during single leg squat and landing tasks. J Electromyogr Kinesiol. 2014;24(5):718–21. https://doi.org/10.1016/j.jelekin.2014.07.007.
154. Crossley KM, Zhang WJ, Schache AG, Bryant A, Cowan SM. Performance on the single-leg squat task indicates hip abductor muscle function. Am J Sports Med. 2011;39(4):866–73. https://doi.org/10.1177/0363546510395456.
155. Ugalde V, Brockman C, Bailowitz Z, Pollard CD. Single leg squat test and its relationship to dynamic knee valgus and injury risk screening. PMR. 2015;7(3):229–35. https://doi.org/10.1016/j.pmrj.2014.08.361.
156. Zeller BL, McCrory JL, Kibler WB, Uhl TL. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. Am J Sports Med. 2003;31(3):449–56.
157. Baldon Rde M, Lobato DF, Carvalho LP, Santiago PR, Benze BG, Serrao FV. Relationship between eccentric hip torque and lower-limb kinematics: gender differences. J Appl Biomech. 2011;27(3):223–32.
158. Willson JD, Ireland ML, Davis I. Core strength and lower extremity alignment during single leg squats. Med Sci Sports Exerc. 2006;38(5):945–52.
159. Claiborne TL, Armstrong CW, Gandhi V, Pincivero DM. Relationship between hip and knee strength and knee valgus during a single leg squat. J Appl Biomech. 2006;22(1):41–50.
160. Stickler L, Finley M, Gulgin H. Relationship between hip and core strength and frontal plane alignment during a single leg squat. Phys Ther Sport. 2015;16(1):66–71. https://doi.org/10.1016/j.ptsp.2014.05.002.
161. Barber-Westin SD, Noyes FR. Risk factors for anterior cruciate ligament injuries in the female athlete. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 344–72.
162. Munro A, Herrington L, Carolan M. Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. J Sport Rehabil. 2012;21(1):7–11.
163. Burnham JM, Yonz MC, Robertson KE, McKinley R, Wilson BR, Johnson DL, Ireland ML, Noehren B. Relationship of hip and trunk muscle function with single leg step-down performance: implications for return to play screening and rehabilitation. Phys Ther Sport. 2016;22:66–73. https://doi.org/10.1016/j.ptsp.2016.05.007.
164. Kline PW, Johnson DL, Ireland ML, Noehren B. Clinical predictors of knee mechanics at return to sport after ACL reconstruction. Med Sci Sports Exerc. 2016;48(5):790–5. https://doi.org/10.1249/MSS.0000000000000856.
165. Ireland ML, Bolgla LA, Noehren B. Gender differences in core strength and lower extremity function during static and dynamic single-leg squat tests. In: Noyes FR, Barber-Westin S, editors. ACL injuries in the female athlete: causes, impacts, and conditioning programs. Berlin: Springer; 2018. p. 239–57. https://doi.org/10.1007/978-3-662-56558-2_13.

Neurocognitive Testing

22

Katherine J. Hunzinger and Charles Buz Swanik

22.1 Introduction

Identifying injury-prone people has been a goal for at least a century, but neurocognitive testing has recently garnered attention in sports medicine to maximize both prevention and rehabilitation intervention strategies [1–3]. Traditionally considered an essential part of concussion management, neurocognitive assessment tools (NCATs) are now included among research and clinical efforts to lessen the impact of musculoskeletal injuries (MSI) [4]. Anterior cruciate ligament (ACL) injuries have been at the epicenter of this MSI research, serving as one of the primary experimental models linking cognitive functions in the nervous to musculoskeletal performance and patient outcomes. While limitations exist among NCATs, there is growing evidence to support its use for enhanced, individualized patient care. Although many paper and pencil neurocognitive/neuropsychological tests have existed for decades and are used for evaluating a wide range of clinical, neurological, and psychiatric issues [5, 6], recently, computerized neurocognitive tests (CNTs) have grown in popularity in the sports medicine community due to their numerous benefits over written tests [7]. The emergence of traumatic brain injury sequelae certainly prompted wide use, with approximately 66.0–95.7% of athletic trainers incorporating CNTs at pre-participation baseline assessments into their concussion management protocols [8–11]. Moreover, many experts now promote the use of CNTs as part of a multi-dimensional baseline injury assessment/screening and recovery program [12].

K. J. Hunzinger (✉) · C. B. Swanik
Department of Kinesiology and Applied Physiology, University of Delaware, Newark, DE, USA

Interdisciplinary Program in Biomechanics and Movement Science, University of Delaware, Newark, DE, USA
e-mail: khunzing@udel.edu

22.2 Neurocognitive Function and ACL Injury

The potential use for neurocognitive testing, to prevent, screen, or otherwise identify those individuals who are either injury prone or may be susceptible to re-injury, has its origins from well-established data on industrial and aviation accident analyses [1, 2, 13]. Much like athletic competition, these “accidents” involve very dynamic environments and high-energy objects, which necessitates the maintenance of situational awareness through complex cognitive processes. While the terms “accidents” or “unintentional injury” denote random events, a more careful examination of causation often leads to human error and not environmental factors [1, 2, 13, 14]. Events such as ACL tears happen faster than the

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_22

blink of an eye [15, 16], so unusually high cognitive demands, combined with emotional dysregulation, can prompt very brief disruptions in concentration, such as fear, startle responses, inattention, or judgement errors that cause a momentary loss of coordination leading to columnar buckling of the knee [17]. This may explain why approximately 75% of ACL tears involve a noncontact mechanism [18] during failed attempts to abruptly decelerate (i.e., cutting or landing) [19–22].

With these typical noncontact ACL (NCACL) injury maneuvers, ground reaction forces can exceed five times the individual's body weight [23]. Thus, complex neuromuscular control strategies for dynamic joint stabilization are required to anticipate and rapidly react to high joint loads in order to mitigate the risk of injury pathomechanics [24–28]. The brain must quickly and continuously integrate vast amounts of visual, vestibular, and somatosensory information and then form an internal model of one's surroundings, before precisely planning for the near-future intricate biomechanics necessary for athletic coordination. The cognitive inability to vigilantly focus attention, generate preparatory motor programs, and refine movement errors may increase the risk of an MSI during strenuous physical activities [29–31]. This is why neurocognitive functions are thought to be factors in the high incidence of NCACL injury mechanisms and risk for MSI after concussion [4, 17, 20].

There are several interrelated neurocognitive factors that likely have crucial roles in sports performance, coordination, and injury [32, 33]. Proper neuromuscular control must constantly fine-tune muscle stiffness regulation strategies, which optimizes the task-specific, visco-elastic properties of muscle for functional performance. The timing and magnitude of these agonist/antagonist co-contractions also help stress-shield ligamentous structures from excessive loading through dynamic restraint, preventing "giving-way" episodes at the joint [34]. In essence, NCACL injuries are the result of improper or insufficient muscle coordination and/or stiffness regulation during unanticipated events [35, 36]. Joint stiffness indicates the measure of resistance provided by the joint to external loading, and in the knee, the quadriceps and hamstring muscles provide dynamic stabilization and can stiffen the joint tenfold [19, 37, 36]. In order to simultaneously maximize both dynamic restraint and functional performance, the central nervous system (CNS) must be able to precisely prepare for and react to sudden, often unanticipated events [19]. These preparatory (feed-forward) and reactive (feedback) neuromuscular control strategies can impart a significant neurocognitive load on the brain [27]. Thus, lower levels of cognitive processing, or the presence of factors that inhibit/limit cognitive function, may lead to altered joint stiffness regulation strategies in the knee, compromise functional joint stability, and heighten injury risk [38, 39].

Neurocognitive functions such as processing speed, reaction times, working memory, and visual-spatial skills were found to be lower in healthy athletes, who later went on to suffer NCACL injuries. These were measured by Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) software at preseason in 160 athletes (80 NCACL, 80 control) [39] (Fig. 22.1). All of the subjects were healthy and had no concussion history but after the standard baseline ImPACT screening went on to suffer their knee injury. Because the neurocognitive exams was actually conducted before their NCACL injury, these data imply that certain executive function skills could aid with attention, situational awareness, anticipatory motor programming, and subsequent reactive muscle stiffness regulation needed to protect the knee during rigorous physical activities [39]. Further evidence supporting the importance of cognition on joint stability was observed when various types of cognitive loading, related to visual/spatial, verbal, or language tasks, were introduced while subjects attempted to protect their knees by reactively stiffening in response to a perturbation [40, 41]. Subjects were instructed to use their thigh muscles to stiffen their knee when it was randomly and suddenly moved by an instrumented motor. However, during this sequence, the subjects also had to perform relatively simple cognitive tasks, such as counting backward by 7. Both

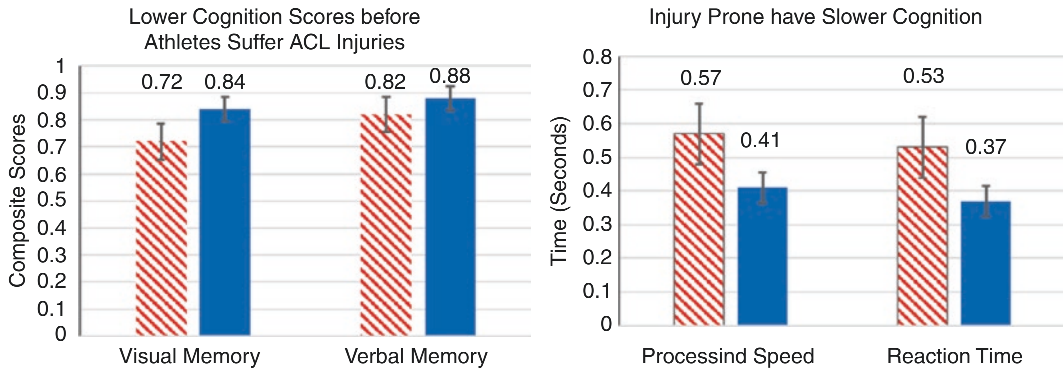


Fig. 22.1 Neurocognitive function in noncontact ACL patients and healthy controls. Neurocognitive scores are worse in certain intercollegiate athletes who suffered noncontact ACL injuries. The data show neurocognitive deficits may be associated with the loss of neuromuscular control and coordination errors leading to musculoskeletal injuries [39]

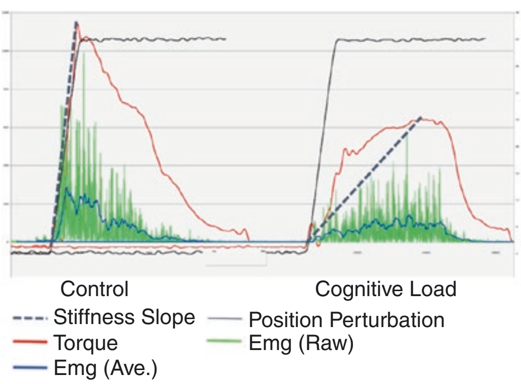


Fig. 22.2 Cognitive loading, either visual/spatial, verbal, or language, significantly decreases the ability of subjects to reactively stiffen the knee joint, in response to a perturbation as evidenced by the decrease stiffness slope from onset to peak torque [35]

males and females suffered significant decreases in muscle activation and joint stiffness, which means they were less able to protect the joint during a cognitive load. If this series of events were replicated during real-world physical activities, the subjects' knees would have significantly lower dynamic restraint during functional types of loads and expose the musculoskeletal structures to injury (Fig. 22.2) [35].

In addition to cognitive loading, sudden unanticipated events (which are common in sport) may also interrupt mental processes and the feed-forward/feedback motor control necessary for optimal temporal/spatial muscle recruitment levels [28, 37, 38]. Unanticipated events, such as sudden sights or sounds, can frequently provoke a startle response within the CNS, yielding widespread, albeit brief, changes in neuromuscular activity [42, 43]. A 2014 study investigating the effects of an acoustic startle on knee stiffness found a significant decrease in knee stability after a startle. Subjects were instructed to quickly "stiffen" their knee when they felt it move. However, one-tenth of a second before the knee was moved, a static noise was emitted through earphones on the subject. The noise provoked a startle response and showed that the quadriceps and hamstring muscle activation strategies responsible for knee joint stiffness regulation, dynamic joint stabilization, and energy absorption were significantly altered. (Fig. 22.3) [19]. The results of this study quantified that unanticipated events, such as a sudden noise, can significantly disrupt knee stiffness regulation required to maintain joint stability, especially if it occurs during the preparatory, planning phase of movements.

This startle phenomenon, albeit a protective mechanism, seizes ones' attention, disrupts planning, and may be impacted or predicted by heightened stress or negative emotions such as fear [44–46]. Fear of re-injury is common among ACL-injured athletes [47]. Even fear-evoking visual stimuli have been shown to increase cortical activation in the frontal regions of the brain as a part of an individual's emotional regulation;

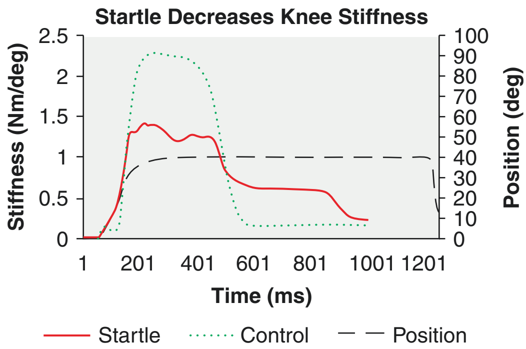


Fig. 22.3 Startling events interrupt muscle stiffness needed to protect against musculoskeletal injury. The data show fear potentiation and unanticipated startling events decreased knee stability, increasing the risk of coordination errors and injury. Knee stiffness in response to an acoustic startle perturbation was decreased by 40% compared to control conditions [19]

cognitive processing in these regions is highly linked to other areas tasked with maintaining sensorimotor system [48–50]. In essence, various unanticipated, emotional, and sensory events can interrupt cognitive processing and function, resulting in altered neuromuscular control patterns needed to maintain muscle stiffness, coordination, and functional joint stability [47, 50, 51].

It should be noted that the regulation of muscles' excitation and inhibition through these mechanisms is highly associated with cognitive processing, previous experiences, and present proprioceptive information, which could be altered following an ACL injury [38, 52, 53]. Individuals with a history of MSI (ACL and/or ankle sprains) have demonstrated changes in the somatosensory cortex and deficits in the excitability of the primary motor cortex, providing a link between MSI and cortical dysfunction [30, 54]. Interestingly, college athletes with MSI have shown cognitive impairments on NCATs 72 h post-injury that are similar to impairments demonstrated following a concussion [3]. These data suggest neurocognitive alterations and/or dysfunction exist following, and potentially before, a lower extremity injury or MSI; these alterations may inhibit proper muscle activation required to maneuver away from and avoid potentially hazardous situations due to lingering disabilities [30].

There is early evidence that the use of cognitive training may be beneficial to the maintenance of joint stability [50]. One study found that after using an online executive function training platform, participants (both controls and ACL reconstruction) were able to improve their cognitive skills. Additionally, the ACL-reconstructed group significantly improved knee function, emotional neurophysiological responses, joint stiffness, and muscle contraction strategies following executive function training [50]. While more studies are needed, these data imply that increased cognitive processing, due to improvements in executive function, is important for emotional regulation and neuromuscular control in order to aid the joint during unanticipated events [50].

22.3 Computerized Neurocognitive Tests

Commercially, there exist a number of CNTs: Automated Neuropsychological Assessment Metrics (ANAM), the Axon Sports CNT (previously known as CogState/Sport), Defense Automated Neurobehavioral Assessment (DANA), and Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) [55, 7, 56]. These tests offer a number of advantages for clinicians and researchers: (1) highly standardized test administration and scoring procedures allowing for consistency in administration across settings; (2) multiple if not infinite alternative test forms; (3) establish cognitive baselines along with serial testing; (4) faster, easier, and cheaper to administer; (5) rapid availability of results without the direct involvement of a neuropsychologist for scoring, administration, and interpretation; (6) ability to mass test; (7) great deal of normative data; and (8) may give insight to future injury risk [6, 57, 58, 7, 11, 39]. Despite the many perceived benefits of NCATs and CNTs, they should not be used for clinical diagnosis, and the vast array of products still have many limitations.

22.3.1 Factors and Limitations Affecting Neurocognitive Assessment Tools

Since 2005, researchers have begun to focus on the psychometric properties of the most commonly used CNTs in clinical use, their limitations, and factors affecting the test [11]. The initial issue with CNTs is upon adapting a test into a computerized form, it has now become a different test from the pen and paper predecessor, which can alter scores and psychometric properties [57]. Additionally, this shift from pen and paper tests necessitates the purchase of additional hardware (i.e., PC, keyboard, stylus, mouse) and potentially requires the purchase of expensive software [59]. Less than optimal test-retest reliabilities have been reported for many subtests of CNTs, along with relatively high false positive rates (i.e., a healthy individual is diagnosed with a concussion) and false negative rates due to low reliabilities [12]; despite this outcome, the use of CNTs is necessitated in sport and clinical practice by the absence of a gold standard diagnostic measure [60]. A final consideration are the numerous factors affecting the tests and individuals' results.

One of the greatest perceived benefits of CNTs is the ability to mass test subjects; however, testing in groups may negatively affect scores and subsequently affect test-retest reliabilities, specifically if follow-up testing (i.e., post-injury or concussion) is conducted individually [6]. Additionally, injury state may influence scores on subtests or entire CNTs. For instance, individuals with a concussion display moderate to large neurocognitive impairments within 1–3 days post-injury on ImPACT when compared to their own baseline [32, 61]; this trend also existed among the Axon Sports CNT [7] and ANAM subtests [3]. Interestingly, concussions are not the only injury to result in altered follow-up scores compared to baseline; post-injury, those with an MSI performed significantly worse than uninjured athletes on ANAM subtests [3]. Athletic injury, be it an MSI or concussion, may produce a degree of cognitive disruption as a result of negative emotional and psychological factors or preexisting vulnerabilities that may surface post-injury affecting CNT scores [3, 4, 39].

NCAT scores and cognitive functioning may be mediated by psychological factors such as depression and anxiety [3]. Additionally, learning disabilities, attention deficit and hyperactivity disorders, psychological distress, and other pre-existing cognitive or neuropsychiatric conditions may produce greater vulnerability in NCAT performance compared to those without comorbidities [11]. As such, an individual's characteristics and psychological health should be taken into consideration when interpreting scores on neurocognitive tests [3, 7, 62].

Lastly, multiple individual factors have been shown to produce neurocognitive deficits. The amount of sleep one receives the night before a test has shown a positive correlation with neurocognitive function [11, 63]. Sleep deprivation in healthy patients has yielded slower reaction times, an increased number of lapses on psychomotor vigilance testing, and reduced working memory, speed, and accuracy on NCATs [63]. Other individual factors like environmental distractions, caffeine consumption, and/or suboptimal or variable effort have also been shown to contribute to random sources of error during NCATs [11].

In summary, critics of CNTs argue that baseline testing does not modify risk (of injury), lacks sufficient psychometrics to support clinical utility, and is influenced by numerous sources of random error [11]. Overall, those who utilize CNTs for the management of concussions should ensure that a CNT is part of a multi-dimensional approach to concussion management [11], CNT has consistent administration protocols, and there is thorough training of those who administer assessments to increase reliability and validity [8]. Over the past decade, data on the psychometric properties of CNTs have grown; these properties are crucial for clinicians to understand when utilizing CNTs in concussion management protocol. As CNTs continue to improve in diagnostic accuracy, they are likely to remain a main component in the multi-dimensional approach to the management of concussion and assessment of cognitive function in injured athletes [11].

22.4 Types of NCATs

22.4.1 Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT)

Created in the 1990s, ImPACT is one type of CNT used for neuropsychological concussion assessment to measure visual and verbal memory, reaction time, and processing speed [32]. It is the most widely used assessment in concussion management, as 89% of NCAA athletic trainers employ this NCAT [8]. In general, it was designed to use randomized alternate test forms in order to minimize practice effects. ImPACT is based on serial testing; athletes complete a baseline or preseason assessment and a follow-up post-injury assessment which is done to determine if the athlete can return safely to activity.

ImPACT has three main components: (1) demographics, (2) post-concussion symptom scale (PCSS), and (3) neurocognitive test modules. In total, there are six neurocognitive test modules, yielding four composite scores and an impulse control score (Table 22.1) [32]. ImPACT takes approximately 25 min and is typically administered by either an athletic trainer, physician, nurse, or a licensed healthcare provider; the results are intended to be interpreted by a healthcare professional.

ImPACT is a commonly used CNT because of its ease of administration via a computer-based program that allows for mass testing decreased staffing requirements, and increased alternate forms of the test compared to paper-based testing [64]. The test has high sensitivity and specificity for concussions, as well as good construct, convergent, and divergent validity with standardized neuropsychological tests in samples of high school and college athletes. Despite its wide use and practical applications, there are a few factors affecting the test that clinicians should keep in mind when utilizing this CNT.

Sleep, or lack of, has been studied extensively in neurocognitive testing. Researchers found a statistically significant difference between neurocognition and sleep duration; athletes who slept <7 h the night before ImPACT performed significantly worse on 3 of the 4 composite scores (all but processing speed) and had more symptoms on the PCSS [63]. Researchers argue that sleep deprivation produces deficits in neurocognitive performance. In healthy individuals, partial sleep deprivation was enough to significantly decrease neurocognitive performance yielding slower reaction times, an increased number of lapses on psychomotor vigilance testing, and reduced working memory speed and accuracy, despite having slept as much as 7 h per night [63].

A perceived benefit of CNTs is the ability to mass test teams and sports at a single time; however, research has shown that high school athletes who were tested in a group setting performed significantly lower across all cognitive measures,

Table 22.1 Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) composite score descriptions and reliability

Composite score	Description	Test-retest reliability[a]
Verbal memory	Average % correct for a word recognition paradigm: a symbol number match task and a letter memory task with an accompanying interference task	0.70
Visual memory	Average % correct for two tasks: a recognition memory task (discrimination of abstract line drawings) and a memory task (identification of a series of illuminated X's and O's)	0.67
Reaction time	Average response time (ms) on a choice reaction time, go/no-go tasks, and the symbol match task	0.79
Processing speed	Weighted average of the three tasks that are done as interference tasks for memory paradigms	0.86
Impulse control	Total number of errors of omission or commission on the choice reaction time and go/no-go tasks. This is used to identify individuals who are not putting forth full effort or are confused by test instructions	N/A

[a]Intraclass correlation coefficient
From Iverson et al. [32]

with higher frequencies of invalid test results [62, 65]. Despite the time and personnel saving benefit, group testing may introduce extraneous error, negatively affecting test performance; these errors may dangerously affect return to play decisions. For example, when utilized as a concussion management protocol, an athlete is typically group tested, and as such, he/she may have lower scores; these lower scores may be falsely predictive of NCACL injury risk. Additionally, if the individual suffers a concussion, he/she will typically be tested in a one-on-one setting which may lead to a better score than baseline and erroneously get cleared for a premature return to play, thus leading to increased risk for musculoskeletal injury because of underlying neurocognitive deficits.

22.4.2 Automated Neuropsychological Assessment Metrics (ANAM)

The ANAM was developed by the Department of Defense in the early 1990s for the US military [66]. It was designed to be a repeatable and sensitive measure of cognitive efficiency and processing speed in both clinical and military populations. ANAM has been used to document impaired cognitive function in individuals with various pathologies (i.e., Parkinson's disease, Alzheimer's, traumatic brain injury, multiple sclerosis, etc.). It is utilized to detect the speed and accuracy of attention, thinking ability, and memory. In the US military, as of 2008, every service member is required to complete the ANAM within 12 months before deployment to be used in the future to identify and/or monitor any changes in function before/after an injury, but not to diagnose [66].

ANAM has been shown to measure the same underlying cognitive constructs as traditional neuropsychological tests measuring cognitive efficiency, information processing speed, working memory, and attention. Reliabilities assessed in military and adolescent samples have ranged from 0.38 to 0.97 depending on the retest interval [67, 66]. The test consists of seven subtests: simple reaction time, simple reaction time (repeated), procedural reaction time, mathematical processing, code substitution learning, code substitution memory, and matching to sample yielding a composite score [68]. Each test provides an accuracy score for the percentage correct, the average time for correct responses, and a throughput score (number of correct responses/minute) [69].

Similar to ImPACT, there have been multiple established differences among groups with the ANAM due to neurocognitive impairments. Researchers found that those with concussions and MSI performed worse than uninjured individuals on the match to sample subtests; additionally, the concussed group performed worse on the code substitution learning and the simple reaction subtests. Researchers subtest that concussions produce a cognitive impairment during the acute recovery period (first 48 h). However, they argue that since the MSI group also had noticeable cognitive impairment, measured by the CNT, in general, athletic injury may produce a degree of cognitive disruption, altering neurocognitive test scores [3]. This disruption in performance may be the result of negative emotion and psychological factors and/or preexisting vulnerabilities that may surface when an athlete is injured. As a result, clinicians should consider injury state when assessing individuals with the ANAM.

22.4.3 Axon Sports Computerized Cognitive Assessment Tool (CogSport/CogState)

Originally called the Cogscreen Aeromedical Edition (Cogscreen-AE), the Axon Sports Computerized Cognitive Assessment Tool was created as an NCAT to be combined with other screening procedures to help improve personnel selections in the Royal Australian Air Force [70]. In recent years, it has been rebranded into the CogSport/CogState but is now referred to as Axon [57]. Axon is designed to help medical providers with return-to-play decisions post-concussions; similar to ImPACT, it is geared toward serial testing (i.e., baseline and repeated following a head injury). Axon measures multiple cognitive areas that are sensitive in concussions, including attention, processing speed, working memory, and learning. Additionally, it boasts acceptable to high reliabilities with an ICC for speed indices ranging from 0.69 to 0.90 at 1 h and 1 week testing intervals [70, 71].

Similar to other CNTs, the benefit of Axon is that it allows for infinite alternative forms and an automated analysis of results. Furthermore, it requires no additional hardware and minimal administration time (15–20 min). The downside to Axon is the fact that there are limited normative data available to clinicians for use and comparison [70, 72].

22.4.4 Defense Automated Neurobehavioral Assessment (DANA)

Created in the late 2000s, the DANA was developed and validated for the US Department of Defense as a tool to support cognitive outcomes measurement for depression, combat fatigue and stress, PTSD, and concussion. It was developed by AnthroTronix as a mobile software application to assess cognitive function. DANA appears to have promise as a next generation NCAT, since it is a JAVA-based mobile application that runs on an Android operating system and is open source and open licensed, allowing versatile use. Furthermore, it is the first FDA-cleared software platform for cognitive and psychological testing. Researchers state it is a durable, portable, and field-hardened CNT that provides a practical means to conduct neurocognitive and neuropsychological assessment in a field deployment setting [55, 56].

There are multiple factors that differentiate the DANA from ANAM and other cognitive assessment batteries. For instance, it can be self-administered either remotely or in-clinic via mobile platform, adding to its versatility. Additionally, its designers utilized public-domain tests with strong scientific literature behind them for the platform; they also selected tests to minimize any demographic and/or training effects. Lastly, the DANA focuses on the measurement of processing speed or "efficiency," which is a building block of higher cognitive function; it also measures cognitive fatigue, a key indicator of clinical state [55]. DANA differs from other CNTs due to the multiple varieties of the test, each measuring reaction time: (1) DANA Rapid: a 5-min battery of three basic reaction time measures; (2) DANA Brief: a 15-min test that includes the DANA Rapid plus additional neurocognitive tests and psychological screening tools for PTSD, depression, and insomnia; and (3) DANA Standard: a 45-min, more comprehensive, batter of neurocognitive and psychological tests [55]. DANA compares favorably to existing NCATs based on reaction time measures. Additionally, the subtest CVs are consistent with CVs for ANAM data collected from various cohorts between 2006 and 2012. Altogether, DANA has adequate reliability and test validity in both service members and nonclinical service members across environments (i.e., jungle, artic, shipboard, altitude, desert) [55, 73].

22.4.5 National Institutes of Health Toolbox Cognition Battery (NIHTB-CB)

A newer CNT, the NIH Toolbox is a comprehensive set of neurobehavioral measurements as a means to assess cognitive, emotional, motor, and sensory functions using an iPad. It is a brief series of cognitive tests, created with the purpose of supplementing measures in longitudinal and epidemiological studies to constitute a "common currency" among researchers [74]. It claims to be the first initiative that was not directed at a specific age group, disease, or arena of us (e.g., hospital, school) [75]. The NIHTB-CB contains seven computerized instruments that measure six ability subdomains important for cognitive health [74].

Cognition is one of the domains assessed by the NIH-TB, with executive function as one of the subdomains. The executive function subdomain includes several constructs including switching/set shifting, inhibitory control and attention, and working memory [74]. The desktop version of the NIHTB has been validated against standard neuropsychological measures in large, diverse populations ranging from 3 to 85 years in age [74, 75]. Additionally, it is positively correlated with clinical tests such as the Preclinical Alzheimer Cognitive Composite (PACC) ($\rho = 0.49$, $P < 0.001$), suggesting alignment with standardized paper-and-pencil tests [76].

The NIHTB-CB is an accessible, brief, and diverse set of instruments with promising psychometrics and can be broadly applied to many research studies and groups across a wide age range. It has been validated as a research test battery, but not clinical use, and it should be noted that it cannot take the place of a screen for cognitive impairment or a full neuropsychological evaluation [74, 75].

22.5 Future Directions: Executive Function Training?

As previously discussed, damage to the ACL can lead to neuromuscular control deficits; these deficits may lead to coordination failures in predicting knee joint loading and regulation of optimal knee joint stiffness, leading to injury [38, 39, 77, 78]. Additionally, functional stability is diminished by fear, a common emotion experienced post-injury. In order to prevent injury through simultaneous mediation of these negative feelings and muscle coordination, an individual requires precise and accurate executive function skills in the brain [15, 79]. With an array of CNTs and NCATs available for use, it is imperative that clinicians maximize the tests' clinical applications; these applications may lie in executive function training.

Components of executive function skills, such as reaction time and working memory, have been related to functional joint instability and injury proneness; preventing injuries is crucial for any sports medicine physician and coach. One way to decrease injury risk is to improve movement patterns and functional ability; this can be achieved through neuromuscular training interventions, which have been shown to improve proprioception, muscle contraction patterns, and knee function in ACLR patients, demonstrating the crucial role of the brain in injury prevention [80–84]. However, another way to decrease injury risk may be executive function training in the form of online platforms and computational brain exercise games including brain speed, attention, fluid intelligence, social cognition, and working memory; these games can be completed on a computer or mobile device at an individual's own pace [50]. Unpublished data suggests that after a 4-week executive function training program (10 h a week for 4 weeks) using BrainHQ applications (Posit Science Corp., San Francisco, CA), individuals improved executive functioning skills, knee functions, and emotional neurophysiological responses, as well as joint stiffness and muscle contraction strategies [50]. These deficits in executive function are also correlated with defensive avoidance and hyperarousal behaviors [85]. Since NCACL injuries happen so rapidly, it is suggested that increased executive function skills could provide sufficient anticipatory motor programming and subsequent reactive muscle stiffness regulation in order to protect the knee during high-velocity maneuvers in sport [39, 50].

References

1. Farmer E, Chambers EG. A study of personal qualities in accident proneness and proficiency. Report 55. London: Industrial Health Research Board Report. H.M.S.O.; 1929.
2. Greenwood M, Woods HM. The incidence of industrial accidents upon individuals: With special reference to multiple accidents. 4. Industrial Fatigue Research Board. London: HM Stationery Office [Darling and Son, Limited, Printers]; 1919.
3. Hutchison M, Comper P, Mainwaring L, Richards D. The influence of musculoskeletal injury on cognition: implications for concussion research. Am J Sports Med. 2011;39(11):2331–7.
4. Herman DC, Zaremski JL, Vincent HK, Vincent KR. Effect of neurocognition and concussion on musculoskeletal injury risk. Curr Sports Med Rep. 2015;14(3):194–9.
5. Bauer RM, Iverson GL, Cernich AN, Binder LM, Ruff RM, Naugle RI. Computerized neuropsychological assessment devices: joint position paper of the American Academy of clinical neuropsychology and the National Academy of neuropsychology. Clin Neuropsychol. 2012;26(2):177–96.

6. Cole WR, Arrieux JP, Schwab K, Ivins BJ, Qashu FM, Lewis SC. Test-retest reliability of four computerized neurocognitive assessment tools in an active duty military population. Arch Clin Neuropsychol. 2013;28(7):732–42.
7. Nelson LD, LaRoche AA, Pfaller AY, Lerner EB, Hammeke TA, Randolph C, Barr WB, Guskiewicz K, McCrea MA. Prospective, head-to-head study of three computerized neurocognitive assessment tools (CNTs): reliability and validity for the assessment of sport-related concussion. J Int Neuropsychol Soc. 2016;22(1):24–37.
8. Covassin T, Elbin RJ, Nakayama Y. Tracking neurocognitive performance following concussion in high school athletes. Phys Sportsmed. 2010;38(4):87–93.
9. Guskiewicz KM, Bruce SL, Cantu RC, Ferrara MS, Kelly JP, McCrea M, Putukian M, McLeod T. National Athletic Trainers' association position statement: management of sport-related concussion. J Athl Train. 2004;39(3):280–97.
10. Meehan WP, d'Hemecourt P, Collins CL, Taylor AM, Comstock RD. Computerized neurocognitive testing for the management of sport-related concussions. J Pediatr. 2012;129(1):38–44.
11. Resch JE, McCrea MA, Cullum CM. Computerized neurocognitive testing in the management of sport-related concussion: an update. Neuropsychol Rev. 2013;23(4):335–49.
12. Farnsworth JL 2nd, Dargo L, Ragan BG, Kang M. Reliability of computerized neurocognitive tests for concussion assessment: a meta-analysis. J Athl Train. 2017;52(9):826–33.
13. Shappell SA, Wiegmann DA. A human error analysis of general aviation controlled flight into terrain accidents occurring between 1990–1998. (Report Number DOT/FAA/AM-03/4). Federal Aviation Administration. Washington DC: Office of Aerospace Medicine; 2003.
14. Xu J, Murphy SL, Kochanek KD, Bastian B, Arias E. Deaths: final data for 2016. Natl Vital Stat Rep. 2018;67(5):1–76.
15. Swanik CB. Brains and sprains: the Brain's role in noncontact anterior cruciate ligament injuries. J Athl Train. 2015;50(10):1100–2.
16. Yasuda K, Erickson AR, Beynnon BD, Johnson RJ, Pope M. Dynamic elongation behavior in the medical collateral and anterior cruciate ligaments during lateral impact loading. J Orthop Res. 1993;11(2):190–8.
17. Boden BP, Torg JS, Knowles SB, Hewett TE. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. Am J Sports Med. 2009;37(2):252–9.
18. Griffin LY, Agel J, Albohm MJ, Arendt EA, Dick RW, Garrett WE, Garrick JG, Hewett TE, Huston L, Ireland ML, Johnson RJ, Kibler WB, Lephart S, Lewis JL, Lindenfeld TN, Mandelbaum BR, Marchak P, Teitz CC, Wojtys EM. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. J Am Acad Orthop Surg. 2000;8(3):141–50.
19. DeAngelis AI, Needle AR, Kaminski TW, Royer TR, Knight CA, Swanik CB. An acoustic startle alters knee joint stiffness and neuromuscular control. Scand J Med Sci Sports. 2015;25(4):509–16.
20. Fleming BC, Ohlen G, Renstrom PA, Peura GD, Beynnon BD, Badger GJ. The effects of compressive load and knee joint torque on peak anterior cruciate ligament strains. Am J Sports Med. 2003;31(5):701–7.
21. Kirkendall DT, Garrett WE Jr. The anterior cruciate ligament enigma. Injury mechanisms and prevention. Clin Orthop. 2000;372:64–8.
22. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am J Sports Med. 2004;32(4):1002–12.
23. McNair PJ, Prapavessis H. Normative data of vertical ground reaction forces during landing from a jump. J Sci Med Sport. 1999;2(1):86–8.
24. Demont RG, Lephart SM, Giraldo JL, Swanik CB, Fu FH. Muscle Preactivity of anterior cruciate ligament-deficient and -reconstructed females during functional activities. J Athl Train. 1999;34(2):115–20.
25. Johansson H, Sjolander P, Sojka P. A sensory role for the cruciate ligaments. Clin Orthop Relat Res. 1991;268:161–78.
26. McClay Davis I, Ireland ML. ACL research retreat: the gender bias. April 6-7, 2001. Meeting report and abstracts. Clin Biomech (Bristol, Avon). 2001;16(10):937–59.
27. Swanik CB, Lephart SM, Giannantonio FP, Fu FH. Reestablishing proprioception and neuromuscular control in the ACL-injured athlete. J Sport Rehabil. 1997;6:182–206.
28. Swanik CB, Lephart SM, Giraldo JL, Demont RG, Fu FH. Reactive muscle firing of anterior cruciate ligament-injured females during functional activities. J Athl Train. 1999;34(2):121–9.
29. Kiesel KB, Butler RJ, Plisky PJ. Prediction of injury by limited and asymmetrical fundamental movement patterns in american football players. J Sport Rehabil. 2014;23(2):88–94.
30. Pietrosimone B, Golightly YM, Mihalik JP, Guskiewicz KM. Concussion frequency associates with musculoskeletal injury in retired NFL players. Med Sci Sports Exerc. 2015;47(11):2366–72.
31. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star excursion balance test as a predictor of lower extremity injury in high school basketball players. J Orthop Sports Phys Ther. 2006;36(12):911–9.
32. Iverson GL, Lovell MR, Collins MW. Interpreting change on ImPACT following sport concussion. Clin Neuropsychol. 2003;17(4):460–7.
33. Nigg BM, Liu W. The effect of muscle stiffness and damping on simulated impact force peaks during running. J Biomech. 1999;32(8):849–56.
34. Lephart SC, Perrin DH, Fu FH, Gieck JH, McCue FC III., Irrgang JJ. Relationship between selected physical characteristics and functional capacity in the anterior cruciate ligament-insufficient athlete. J Orthop Sports Phys Ther. 1992;16(4):174–81.

35. Kim AS, Needle AR, Thomas SJ, Higginson CI, Kaminski TW, Swanik CB. A sex comparison of reactive knee stiffness regulation strategies under cognitive loads. Clin Biomech (Bristol, Avon). 2016;35:86–92.
36. Wojtys EM, Huston LJ, Schock HJ, Boylan JP, Ashton-Miller JA. Gender differences in muscular protection of the knee in torsion in size-matched athletes. J Bone Joint Surg Am. 2003;85-A(5):782–9.
37. Markolf KL, Graff-Radford A, Amstutz HC. In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. J Bone Joint Surg Am. 1978;60(5):664–74.
38. Swanik CB, Lephart SM, Swanik KA, Stone DA, Fu FH. Neuromuscular dynamic restraint in women with anterior cruciate ligament injuries. Clin Orthop Relat Res. 2004;(425):189–99.
39. Swanik CB, Covassin T, Stearne DJ, Schatz P. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. Am J Sports Med. 2007;35(6):943–8.
40. Adam JJ, Paas FG, Buekers MJ, Wuyts IJ, Spijkers WA, Wallmeyer P. Gender differences in choice reaction time: evidence for differential strategies. Ergonomics. 1999;42(2):327–35.
41. Jones RN, Gallo JJ. Education and sex differences in the mini-mental state examination: effects of differential item functioning. J Gerontol B Psychol Sci Soc Sci. 2002;57(6):P548–58.
42. Davis M. The mammalian startle response. In: Eaton RC, editor. Neural mechanisms of startle behavior. New York: Plenum; 1984. p. 287–351.
43. Koch M. The neurobiology of startle. Prog Neurobiol. 1999;59(2):107–28.
44. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2013;41(7):1549–58.
45. Gobbi A, Bathan L, Boldrini L. Primary repair combined with bone marrow stimulation in acute anterior cruciate ligament lesions: results in a group of athletes. Am J Sports Med. 2009;37(3):571–8.
46. Lee DY, Karim SA, Chang HC. Return to sports after anterior cruciate ligament reconstruction - a review of patients with minimum 5-year follow-up. Ann Acad Med Singap. 2008;37(4):273–8.
47. Chmielewski TL, Jones D, Day T, Tillman SM, Lentz TA, George SZ. The association of pain and fear of movement/reinjury with function during anterior cruciate ligament reconstruction rehabilitation. J Orthop Sports Phys Ther. 2008;38(12):746–53.
48. Amaral DG. The functional organization of perception and movement. In: Kandel ER, Schwartz JH, Jessell JM, Siegelbaum SA, Hudspeth AJ, Mack S, editors. Principles of neural science. 5th ed. New York: McGraw-Hill; 2013. p. 356–69.
49. Amaral DG, Strick PL. The organization of the central nervous system. In: Kandel ER, Schwartz JH, Jessell JM, Siegelbaum SA, Hudspeth AJ, Mack S, editors. Principles of neural science. 5th ed. New York: McGraw-Hill; 2013. p. 337–55.
50. An YW (2016) Neuromechanical links between cognition, fear and joint instability. (Unpublished doctoral dissertation) University of Delaware, Newark, DE.
51. Lentz TA, Zeppieri G Jr, George SZ, Tillman SM, Moser MW, Farmer KW, Chmielewski TL. Comparison of physical impairment, functional, and psychosocial measures based on fear of reinjury/lack of confidence and return-to-sport status after ACL reconstruction. Am J Sports Med. 2015;43(2):345–53.
52. Riemann BL, Lephart SM. The sensorimotor system, part II: the role of proprioception in motor control and functional joint stability. J Athl Train. 2002;37(1):80.
53. Medeiros-Ward N, Watson JM, Strayer DL. On supertaskers and the neural basis of efficient multitasking. Psychon Bull Rev. 2015;22(3):876–83.
54. An YW, DiTrani Lobacz A, Lehmann T, Baumeister J, Rose WC, Higginson JS, Rosen J, Swanik CB. Neuroplastic changes in anterior cruciate ligament reconstruction patients from neuromechanical decoupling. Scand J Med Sci Sports. 2019;29(2): 251–8. https://doi.org/10.1111/sms.13322. Epub 2018 Nov 7.
55. Lathan C, Spira JL, Bleiberg J, Vice J, Tsao JW. Defense automated neurobehavioral assessment (DANA)-psychometric properties of a new field-deployable neurocognitive assessment tool. Mil Med. 2013;178(4):365–71.
56. Russo CR, Lathan CE. An evaluation of the consistency and reliability of the defense automated neurocognitive assessment tool. Appl Psychol Meas. 2015;39(7):566–72.
57. De Marco AP, Broshek DK. Computerized cognitive testing in the Management of Youth Sports-Related Concussion. J Child Neurol. 2016;31(1):68–75.
58. Howell DR, Lynall RC, Buckley TA, Herman DC. Neuromuscular control deficits and the risk of subsequent injury after a concussion: a scoping review. Sports Med (Auckland, NZ). 2018;48(5):1097–115.
59. Collie A, Darby D, Maruff P. Computerised cognitive assessment of athletes with sports related head injury. Br J Sports Med. 2001;35(5):297–302.
60. Broglio SP, Katz BP, Zhao S, McCrea M, McAllister T. Test-retest reliability and interpretation of common concussion assessment tools: findings from the NCAA-DoD CARE consortium. Sports Med (Auckland, NZ). 2018;48(5):1255–68.
61. Iverson G, Franzen M, Lovell M, Collins M. Construct validity of ImPACT in athletes with concussions. Arch Clin Neuropsychol. 2004;19(7):961–2.
62. Lichtenstein JD, Moser RS, Schatz P. Age and test setting affect the prevalence of invalid baseline scores on neurocognitive tests. Am J Sports Med. 2014;42(2):479–84.
63. McClure DJ, Zuckerman SL, Kutscher SJ, Gregory AJ, Solomon GS. Baseline neurocognitive testing in sports-related concussions: the importance of a prior night's sleep. Am J Sports Med. 2014;42(2): 472–8.
64. Nakayama Y, Covassin T, Schatz P, Nogle S, Kovan J. Examination of the test-retest reliability of a computerized neurocognitive test battery. Am J Sports Med. 2014;42(8):2000–5.

65. Moser RS, Schatz P, Neidzwski K, Ott SD. Group versus individual administration affects baseline neurocognitive test performance. Am J Sports Med. 2011;39(11):2325–30.
66. Vincent AS, Roebuck-Spencer T, Gilliland K, Schlegel R. Automated neuropsychological assessment metrics (v4) traumatic brain injury battery: military normative data. Mil Med. 2012;177(3):256–69.
67. Cernich A, Reeves D, Sun W, Bleiberg J. Automated neuropsychological assessment metrics sports medicine battery. Arch Clin Neuropsychol. 2007;22(Suppl 1):S101–14.
68. Cole WR, Arrieux JP, Dennison EM, Ivins BJ. The impact of administration order in studies of computerized neurocognitive assessment tools (NCATs). J Clin Exp Neuropsychol. 2017;39(1):35–45.
69. Segalowitz SJ, Mahaney P, Santesso DL, MacGregor L, Dywan J, Willer B. Retest reliability in adolescents of a computerized neuropsychological battery used to assess recovery from concussion. Neuro Rehabilitation. 2007;22(3):243–51.
70. Westerman R, Darby DG, Maruff P, Collie A. Computer-assisted cognitive function assessment of pilots. ADF Health. 2001;2:29–36.
71. Collie A, Maruff P, Makdissi M, McCrory P, McStephen M, Darby D. CogSport: reliability and correlation with conventional cognitive tests used in postconcussion medical evaluations. Clin J Sport Med. 2003;13(1):28–32.
72. Arrieux JP, Cole WR, Ahrens AP. A review of the validity of computerized neurocognitive assessment tools in mild traumatic brain injury assessment. Concussion (London, England). 2017;2(1):Cnc31.
73. Haran FJ, Dretsch MN, Bleiberg J. Performance on the Defense automated neurobehavioral assessment across controlled environmental conditions. Appl Neuropsychol Adult. 2016;23(6):411–7.
74. Weintraub S, Dikmen SS, Heaton RK, Tulsky DS, Zelazo PD, Bauer PJ, Carlozzi NE, Slotkin J, Blitz D, Wallner-Allen K, Fox NA, Beaumont JL, Mungas D, Nowinski CJ, Richler J, Deocampo JA, Anderson JE, Manly JJ, Borosh B, Havlik R, Conway K, Edwards E, Freund L, King JW, Moy C, Witt E, Gershon RC. Cognition assessment using the NIH toolbox. Neurology. 2013;80(11 Suppl 3):S54–64.
75. Weintraub S, Dikmen SS, Heaton RK, Tulsky DS, Zelazo PD, Slotkin J, Carlozzi NE, Bauer PJ, Wallner-Allen K, Fox N, Havlik R, Beaumont JL, Mungas D, Manly JJ, Moy C, Conway K, Edwards E, Nowinski CJ, Gershon R. The cognition battery of the NIH toolbox for assessment of neurological and behavioral function: validation in an adult sample. J Int Neuropsychol Soc. 2014;20(6):567–78.
76. Buckley RF, Sparks KP, Papp KV, Dekhtyar M, Martin C, Burnham S, Sperling RA, Rentz DM. Computerized cognitive testing for use in clinical trials: a comparison of the NIH toolbox and cogstate C3 batteries. J Prev Alzheimer’s Dis. 2017;4(1):3–11.
77. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. J Athl Train. 2007;42(2):311–9.
78. Hootman JM, Albohm MJ. Anterior cruciate ligament injury prevention and primary prevention of knee osteoarthritis. J Athl Train. 2012;47(5):589–90.
79. Gyurak A, Goodkind MS, Kramer JH, Miller BL, Levenson RW. Executive functions and the downregulation and up-regulation of emotion. J Cognition Emotion. 2012;26(1):103–18.
80. Beard DJ, Dodd CAF, Trundle HR, Simpson AHRW. Proprioception enhancement for anterior cruciate ligament deficiency. A prospective randomised trial of two physiotherapy regimes. J Bone Joint Surg. 1994;76B(4):654–9.
81. Fitzgerald GK, Axe MJ, Snyder-Mackler L. A decision-making scheme for returning patients to high-level activity with nonoperative treatment after anterior cruciate ligament rupture. Knee Surg Sports Traumatol Arthrosc. 2000;8(2):76–82.
82. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med. 1999;27(6):699–706.
83. Risberg MA, Holm I, Myklebust G, Engebretsen L. Neuromuscular training versus strength training during first 6 months after anterior cruciate ligament reconstruction: a randomized clinical trial. Phys Ther. 2007;87(6):737–50.
84. Risberg MA, Holm I. The long-term effect of 2 postoperative rehabilitation programs after anterior cruciate ligament reconstruction: a randomized controlled clinical trial with 2 years of follow-up. Am J Sports Med. 2009;37(10):1958–66.
85. Mahan AL, Ressler KJ. Fear conditioning, synaptic plasticity and the amygdala: implications for posttraumatic stress disorder. Trends Neurosci. 2012;35(1):24–35.

Part VI

Psychological Readiness

23 Validated Questionnaires to Measure Return to Sport and Psychological Factors

Sue Barber-Westin and Frank R. Noyes

23.1 Introduction

This chapter reviews commonly used scales that have been used to rate athletic activities for a variety of knee injuries and disorders. The instruments are analyzed according to their strengths and potential biases as well as their measured reliability, validity, and responsiveness properties. In addition, several validated questionnaires are provided that may be used to determine an athlete's psychological status both before surgery and postoperatively. Psychological factors such as fear of reinjury, anxiety, depression, and preoperative stress are common barriers to RTS and overall patient satisfaction after serious knee injuries and operations such as anterior cruciate ligament (ACL) reconstruction [1–12]. The detection of these problems allows for early implementation of counseling and other treatments that may prevent these issues from negatively affecting the overall outcome of surgery and physical therapy.

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

23.2 Sports Activity Scales

23.2.1 Cincinnati Sports Activity Scale

The Cincinnati Sports Activity Scale is one component of the comprehensive Cincinnati Knee Rating System (CKRS) [13, 14]. The CKRS measures pain, swelling, giving-way, functions of sports and daily activities, sports activity levels, patient perception of the knee condition, range of knee motion, joint effusion, tibiofemoral and patellofemoral crepitus, knee ligament subluxations, compartment narrowing on radiographs, and lower limb symmetry during single-leg hop tests. The CKRS has been validated for a variety of knee problems [14, 15] and although initially designed for ACL cohorts, it is also useful for patients who have undergone other operative procedures such as articular cartilage restorative procedures [16], meniscus repairs or transplants, osteotomies, or patellofemoral procedures.

The Sports Activity Scale of the CKRS was first introduced in 1989 after an analysis of existing scales at that time period detected multiple biases and potential sources of error in reporting the outcome of ACL reconstruction [17]. The goal in the development of the Sports Activity Scale was to distinguish among categories of athletic activities in a manner that allowed

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_23

investigators to apply the rating in a uniform manner to any type of athletic activity. Two criteria were selected to determine this rating. First, the frequency of participation was determined using a four-level gradient that assigned patients to a subgroup depending upon the number of days in a week (or month) of sports participation (Table 23.1). Second, the knee functions that occurred during various sports activities were sorted into three subgroups, from the most difficult knee motions of jumping, hard pivoting, and cutting; to running, twisting, and turning; and finally to activities that do not involve running, twisting, or jumping (e.g., swimming and cycling).

Sorting of sports activities according to frequency and intensity eliminates the ambiguous classification of athletes into categories (such as recreational or competitive) allowing all levels of athletes to be categorized on this scale. Although some examples of sports are listed under the various subgroups, any athletic activity may be placed into the scale according to the knee functions that occur during that particular activity. The reporting of the patient responses to the Cincinnati Sports Activity Scale may be shown as a distribution according to either frequency or intensity of activities (Table 23.2). An average score should not be calculated from this scale, because the data are categorical in nature.

Table 23.1 Cincinnati sports activity scale [17]. Circle the number that describes your level of sports activity at this time

Level I (participates 4–7 days/week)	
100	Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
95	Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
90	No running, twisting, jumping (cycling, swimming)
Level II (participates 1–3 days/week)	
85	Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
80	Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
75	No running, twisting, jumping (cycling, swimming)
Level III (participates 1–3 times/month)	
65	Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
60	Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
55	No running, twisting, jumping (cycling, swimming)
Level IV (no sports)	
40	I perform activities of daily living without problems
20	I have moderate problems with activities of daily living
0	I have severe problems with activities of daily living; on crutches, full disability

Table 23.2 Sports activity by subgroup using the Cincinnati sports activity scale [77]

	Preoperatively (%)		Follow-up (%)	
	Chronic	Acute	Chronic	Acute
Type of sport				
Jumping, pivoting, cutting	9	76	16	50
Running, twisting, turning	21	10	23	17
Swimming, bicycling	21	14	47	17
Activities of daily living only	49	9	14	17
Change from preoperative levels				
Increased level, no symptoms			54	3
Same level, no symptoms			9	50
Decreased level, no symptoms			12	27
Playing with symptoms			11	3
No participation due to knee condition			12	0
No participation non knee-related factors			2	17

Table 23.3 Assessing change in activity levels with the Cincinnati sports scale [17]

Check the ONE line that best describes the change you have had in sports activities since your injury or surgery. My sports activities have
Increased _____ I have no/slight problems _____ I have moderate/significant problems Not changed _____ I have no/slight problems _____ I have moderate/significant problems Decreased _____ I have no/slight problems _____ I have moderate/significant problems _____ For reasons not related to my knee Stopped, given up all sports _____ I have moderate/significant problems when I play sports _____ For reasons not related to my knee

A second component of the Cincinnati Sports Activity Scale is the change that occurs in activity levels between treatment periods (Table 23.3). The format is designed to determine changes in sports activities due to either knee-related or non-knee-related reasons and to detect knee abusers. The third component of the assessment of activities is the rating of six individual functions that place varying loads on the knee joint (Table 23.4). Functions of sports are analyzed separately from those of daily activities to assess limitations in all patients, not just those participating in athletics. Each function is determined using a four-level gradient whose terminology was selected to decrease the subjective component inherent in this type of analysis.

The reliability of the entire CKRS, including the Sports Activity Scale, was performed in a group of 50 patients who had a variety of chronic knee injuries and disorders (meniscal tears, knee ligament tears, patellofemoral complaints, and degenerative joint disease) and 50 healthy volunteers [14]. Validity and responsiveness testing were conducted on a group of 250 patients who were prospectively followed after ACL bone-patellar tendon-bone autogenous reconstruction a mean of 27 months (range, 23–74 months) postoperatively.

The reliability of the Sports Activity Scale showed large effect sizes (ES), with intraclass correlation coefficients (ICC) of 0.98 in both groups of subjects. Content validity of the scale showed minimal floor and ceiling effects and item-discriminant validity was found to be adequate. Responsiveness testing revealed adequate standardized response mean of 1.37 and a large ES of 1.91. Other investigators have also reported adequate reliability (ICC, >0.80), validity, and responsiveness of this scale [15, 16, 18–20].

Table 23.4 Assessment of individual functions with the Cincinnati sports scale [17]

Check the problems you have during each of the following activities
1. Walking _____ Normal, unlimited _____ Some limitations _____ Only 3–4 blocks possible _____ Less than 1 block; cane, crutch
2. Stairs _____ Normal, unlimited _____ Some limitations _____ Only 11–30 steps possible _____ Only 1–10 steps possible
3. Squatting/kneeling _____ Normal, unlimited _____ Some limitations _____ Only 6–10 possible _____ Only 0–5 possible
4. Straight running _____ Fully competitive _____ Some limitations, guarding _____ Definite limitations, ½ speed _____ Not able to do
5. Jumping/landing _____ Fully competitive _____ Some limitations, guarding _____ Definite limitations, ½ speed _____ Not able to do
6. Hard twists/cuts/pivots _____ Fully competitive _____ Some limitations, guarding _____ Definite limitations, ½ speed _____ Not able to do

23.2.2 Tegner Activity Scale

Tegner and Lysholm [21] developed one of the first rating scales to quantify activity levels in patients with ACL ruptures (Table 23.5). The Tegner Activity Scale classifies both sports and work activities into one questionnaire using an 11-level gradient. Competitive sports make up

Table 23.5 Tegner activity score [21]

Level number	Level descriptor	Examples of activities
10	Competitive sports	Soccer—national and international elite
9	Competitive sports	Soccer, lower divisions, ice hockey, wrestling, gymnastics
8	Competitive sports	Bandy, squash, badminton, athletics (jumping, etc.), downhill skiing
7	Competitive sports	Tennis Athletics (running) Motorcross, speedway Handball Basketball
	Recreational sports	Soccer, bandy, ice hockey, squash, athletics (jumping), cross-country track both recreational and competitive
6	Recreational sports	Tennis, badminton, handball, basketball, downhill skiing, jogging, at least five times per week
5	Work	Heavy labor (e.g., building, forestry)
	Competitive sports	Cycling, cross-country skiing
	Recreational sports	Jogging on uneven ground at least twice weekly
4	Work	Moderately heavy labor (e.g., truck driving, heavy domestic work)
	Recreational sports	Cycling, cross-country skiing, jogging on uneven ground at least twice weekly
3	Work	Light labor (e.g., nursing)
	Competitive and recreational sports	Swimming
	Walking	Walking in forest possible
2	Work	Light labor
	Walking	Walking on uneven ground possible but impossible to walk in forest
1	Work	Sedentary work
	Walking	Walking on even ground possible
0	Sick leave or disability pension because of knee problems	

the top three levels (levels 10–8), competitive and recreational sports categories both appear in level 7 and "other recreational sports" make up level 6. Levels 5 through 1 combine work and sports together, and level 0 indicates sick leave or disability due to the knee condition. The original publication did not provide reliability, validity, or responsiveness data of this scale.

Several problems are incurred with this activity rating instrument. First, work activities are rated within the same scale as sports activities. Patients who work in heavy-labor occupations are only awarded a level 5 (out of a possible 10), but the analysis of the stress on the lower limb in some of these occupations would probably show that these knees are functioning at a level equivalent to that of competitive athletes. They should not be awarded a lower level simply because they are not athletes or did not return to highly competitive sports. Athletics and occupational activities should be measured on separate rating scales.

Second, this scale does not separate various sports levels according to the frequency of participation or the intensity of the sport, which is determined by accounting for the forces placed on the lower extremity. For instance, only national and international elite soccer players are listed on level 10, whereas basketball is listed on a level 7. In the United States, it could be argued that competitive high school, collegiate, or professional basketball players are asked to place similar demands on the knee joint and lower extremity as elite soccer players. For patients who play or return to sports not listed on the scale, problems are incurred in trying to determine exactly which level accurately defines their sport. Third, this scale does not allow an assessment of a change in athletic participation between time periods owing to a change in lifestyle (e.g., graduated from school and no longer participate in a league). In addition, one cannot detect knee abusers in either the sport or the work levels.

Independent investigations assessed the reliability, validity, and responsiveness of the Tegner scale for a variety of knee injuries. Briggs and coworkers [22] determined its reliability, validity, and responsiveness in 122 patients with meniscus injuries. The scale was found to have adequate reliability (ICC, 0.817), content validity (no ceiling or floor effects), criterion validity with the Medical Outcomes Short Form-12 Health Survey (SF-12), and construct validity. However, only moderate ES and standardized response mean values were reported. The investigators concluded that the scale measures only moderate changes in activity levels, and noted that patients in the United States may have difficulty completing the scale because it was designed for sports commonly played in Europe.

Paxton and associates [23] assessed the reliability and validity of this scale in 153 patients followed 2–5 years after an acute patellar dislocation. The scale was found to have adequate reliability (ICC, 0.92) and content validity. Briggs and colleagues [24] found the Tegner scale had adequate reliability, validity, and responsiveness following ACL injury and reconstruction.

Ebert and associates [25] reported that the Tegner scale was less responsive to change following articular cartilage restorative procedures in comparison with the Knee Injury and Osteoarthritis Outcome Score subscales of sport/recreation and quality of life. There was no strong evidence that a change in the Tegner scale was associated with patient satisfaction of the outcome of the operation. Naal and coworkers [26] compared data from three activity rating scales (Tegner, University of California, Los Angeles [UCLA] [27], and Marx Activity Rating Scale [28]) in patients who underwent total joint arthroplasty. Physical activity was assessed using the "last 7 days" version of the International Physical Activity Questionnaire (IPAQ) [29]. The Tegner scale was found to be reliable and had acceptable validity in patients undergoing total knee arthroplasty. However, this scale had lower correlation coefficients and lower completion rates than the UCLA scale and was unable to discriminate between patients who were sufficiently active (moderate and vigorous activity levels according to IPAQ classification) and those who were insufficiently active.

23.2.3 Marx Sports Activity Scale

Marx et al. [28] developed a sports activity rating scale to use as a general research tool to determine the outcome of a variety of knee injuries and operations (Table 23.6). This scale takes into account the frequency of participation and intensity of the activity. Four separate activities are rated: running, cutting, decelerating, and pivoting. Reliability and construct validity were assessed in 40 volunteers with no history of knee problems. The scale showed acceptable reliability (ICC, 0.97) and correlated with the Tegner,

Table 23.6 Marx activity rating scale [28]. Indicate how often you performed each activity in your healthiest and most active state, in the past year

	<1×/ month	1×/ month	1×/ week	2–3×/ week	≥4×/ week
Running while playing a sport or jogging					
Cutting: changing directions while running					
Decelerating: coming to a quick stop while running					
Pivoting: turning your body with your foot planted while playing a sport; such as skiing, skating, kicking, throwing, hitting a ball (golf, tennis, squash)					

Scoring: <1×/month = 0 points, 1×/month = 1 point each, 1×/week = 2 points each, 2–3×/week = 3 points each, and ≥4×/week = 4 points each; maximum score 16

Cincinnati, and Daniel sports activity scales. Responsiveness testing was not completed.

Naal et al. [26] compared data from three activity rating scales (Tegner, UCLA [27], and Marx Activity Rating Scale [28]) in patients who underwent total joint arthroplasty. The Marx Activity Rating Scale was found to be reliable and had acceptable validity in patients undergoing TKA. However, this scale had the weakest correlation coefficients with other scales, had large floor effects, and was unable to discriminate between patients who were sufficiently active (moderate and vigorous activity levels according to IPAQ classification) and those who were insufficiently active. Although this scale is useful in rating activities that involve the specific motions selected by the authors, it cannot rate low-impact activities such as swimming, bicycling, or low-impact aerobics. If a patient swam or bicycled several times a week, he or she would receive 0 out of a possible 16 points on this scale.

23.2.4 IKDC Sports Scale

In 1995, the International Knee Documentation Committee (IKDC) [30] published an activity rating that consisted of four levels: strenuous activity involving jumping, pivoting, and hard cutting (football, soccer); moderate activity or heavy manual work (skiing, tennis); light activity or light manual work (jogging, running); and sedentary activity (housework, activities of daily living). Then, a few years later, the 2000 IKDC Subjective Knee Evaluation Form was published [31] which included a sports activity rating. Patients indicate their regular highest level of activity of either very strenuous activities like jumping or pivoting as in basketball or soccer; strenuous activities like heavy physical work, skiing or tennis; moderate activities like moderate physical work, running or jogging; light activities like walking, housework or yard work; or unable to perform any of these activities due to knee pain.

The sports activity scale is one of twenty items on the Subjective Knee Evaluation form, whose numerical values are summed and divided by the maximum possible score. Although acceptable reliability, validity, and responsiveness values have been published for the form in its entirety [31, 32], no data is available for just the sports activity scale. Additional problems include failure to account for frequency of sports participation and the combination of work and sports activities in three of the five levels.

23.3 Psychological Questionnaires (Table 23.7)

23.3.1 ACL-Return to Sport After Injury (ACL-RSI) Scale

The ACL-RSI scale was introduced by Webster et al. [33] in 2008 as a means of measuring the psychological impact of returning to sports after ACL reconstruction. The authors tested the 12-item questionnaire (Table 23.8) in 220 patients a mean of 22 months postoperatively. The items on the scale were identified by the literature as associated with RTS and included emotions, confidence in performance, and risk appraisal. Acceptable reliability was reported (Cronbach's alpha = 0.92). Patients who had not RTS scored significantly lower on the scale than those who returned ($P < 0.001$), indicating a more negative psychological response was associated with failure to return to sport. Overall, 69% of subjects who RTS scored significantly higher (mean, 70 points) than 31% of subjects who did not RTS (mean, 46 points). Since then, the ACL-RSI scale has been translated into several languages, including Chinese [34], Portuguese [35], Turkish [36], Dutch [37], French [38], and Swedish [39].

Webster and Feller [40] recently published a shortened version of the ACL-RSI, composed of six items (Table 23.9). A group of 535 patients who had undergone ACL reconstruction participated in the scale reduction component of the study, and the second group of 250 ACL-reconstructed patients participated in the predictive validation component of

Table 23.7 Validated psychological and psychosocial questionnaires

Questionnaire	Items assessed
ACL-return to sport after injury (ACL-RSI) [33]	Emotions, confidence in performance, reinjury risk appraisal
Tampa scale for Kinesiophobia (TSK) [41, 42]	Fear of movement/reinjury
Tampa scale for Kinesiophobia modified (TSK-11) [47]	Fear of movement/reinjury
Knee self-efficacy scale (K-SES) [57]	Daily activities, sports and leisure activities, physical activities, knee function in the future
Injury-psychological readiness to return to sport scale [61]	Confidence in the ability to play, performance
Reinjury anxiety inventory [63]	Anxieties about rehabilitation and return to sport
Quick inventory of depressive symptomatology [65]	Depression, sleep, appetite/weight
Sports rehabilitation locus of control (SRLC) [78]	Internal, powerful, and chance items
Multidimensional health locus of control scale (MHLC) [68]	Internal locus of control
State-trait anxiety inventory [74]	State anxiety: how an athlete feels currently about various situations that may influence anxiety levels (i.e., not at all, very much so); temporary condition Trait anxiety: how an athlete feels in general toward various situations that may influence anxiety levels (i.e., almost never, almost always); long-standing condition

Table 23.8 ACL-return to sport after injury (ACL-RSI) scale questions [33]

1. Are you confident that you can perform at your previous level of sports participation?
2. Do you think you are likely to reinjure your knee by participating in your sport?
3. Are you nervous about playing your sport?
4. Are you confident that your knee will not give way by playing your sport?
5. Are you confident that you could play your sport without concern for your knee?
6. Do you find it frustrating to have to consider your knee with respect to your sport?
7. Are you fearful of reinjuring your knee by playing your sport?
8. Are you confident about your knee holding up under pressure?
9. Do thoughts of having to go through surgery and rehabilitation again prevent you from playing your sport?
10. Are you afraid of accidentally injuring your knee by playing your sport?
11. Are you confident about your ability to perform well at your sport?
12. Are you relaxed about playing your sport?

All questions answered by circling one number from 0 to 100, where 0 = not at all and 0 = extremely

Table 23.9 ACL-return to sport after injury scale (short version) [40]

1. Are you confident that you can perform at your previous level of sports participation?
2. Do you think you are likely to reinjure your knee by participating in your sport?
3. Are you nervous about playing your sport?
4. Are you confident that you could play your sport without concern for your knee?
5. Do you find it frustrating to have to consider your knee with respect to your sport?
6. Are you fearful of reinjuring your knee by playing your sport?

All questions answered by circling one number from 0 to 100, where 0 = not at all and 0 = extremely the investigation. All patients completed the original ACL-RSI scale. The authors reported that the original scale had high internal consistency, which suggested that item redundancy was present. This allowed an item selection process, which reduced the number of questions from twelve to six. There were significant differences in the scores between patients who RTS and those who had not for both the original scale (81.4 ± 15 and 51.7 ± 25; $P < 0.0001$) and the short version (77.8 ± 18 and 47.9 ± 26; $P < 0.0001$). At 6 months postoperatively, the ACL-RSI scores for both the original and short versions had fair to good predictive ability for the 12-month RTS outcomes. The authors recommended use of the short version, especially for busy clinical settings to identify athletes who may find RTS challenging.

23.3.2 Tampa Scale for Kinesiophobia (TSK) [41, 42]

The Tampa Scale for Kinesiophobia (TSK) was first described in 1995 by Vlaeyen et al. [42] in a population of chronic low-back pain patients. Subsequent studies have demonstrated adequate reliability, validity, and responsiveness of the TSK in a variety of chronic pain cohorts [43–46]. The scale was slightly modified by Kvist et al. [41] to measure fear of reinjury upon RTS after ACL reconstruction (Table 23.10). A shortened version, the TSK-11, was introduced by Woby et al. in 2005 [47] who reported good internal consistency, reliability, responsiveness, concurrent validity, and predictive validity for both the original and shortened scales. Tkachuk and Harris [48] also investigated the psychometric properties of the shortened TSK-11 in 276 chronic pain patients. The authors reported that the scale had acceptable levels of internal consistency, as well as discriminant, concurrent criterion-related, and incremental validity. Subscales predicted physical performance and perceived disability. The TSK has been translated into multiple languages including Portuguese [49], Swedish [50], Spanish [51], Norwegian [52], German [53], Chinese [54], Persian [55], and Italian [56]

23.3.3 Knee Self-Efficacy Scale (K-SES) [57]

Thomee et al. [57] developed the Knee Self-Efficacy (K-SES) scale (Table 23.11) to measure perceived self-efficacy in patients with an ACL

Table 23.10 Tampa scale for Kinesiophobia (TSK) [42]

1. I'm afraid that I might injure myself if I exercise
2. If I were to try to overcome it, my pain would increase
3. My body is telling me I have something dangerously wrong
4. My knee trouble would probably be relieved if I were to exercise
5. People aren't taking my medical condition seriously enough
6. My injury has put my body at risk for the rest of my life
7. Pain always means I have injured my body
8. Just because something aggravates my knee trouble does not mean it is dangerous
9. I am afraid that I might injure myself accidentally
10. Simple being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my injured leg from worsening
11. I wouldn't have this much knee trouble if there weren't something potentially dangerous going on in my body
12. Although my condition is painful, I would be better off if I were physically active
13. Pain lets me know when to stop exercising so that I don't injure myself
14. It's really not safe for a person with a condition like mine to be physically active
15. I can't do all the things normal people do because it's too easy for me to get injured again
16. Even though my injured knee is causing me a lot of pain, I don't think it's actually dangerous
17. No one should have to exercise when he/she gets injured

Questions scored on a 4-point Likert scale from "strongly disagree" to "strongly agree", except questions 4, 8, 12, and 16 that are inversely scored. Total scores range from 17 to 68, with higher scores reflecting greater fear of movement/(re)injury
Scale modified by Kvist et al. [41] for knee injuries

injury. Reliability was found to be adequate (ICC, 0.75), as were several validity factors (face, content, construct, and convergent). In a second study, Thomee et al. [58] reported good responsiveness in both ACL-deficient and ACL-reconstructed patients. Mean K-SES scores increased in ACL-deficient knees from just after injury to 1 year later (3.9 and 6.8, respectively; $P < 0.001$) and in ACL-reconstructed knees from preoperatively to 1 year postoperatively (5.0 and 7.6, respectively; $P < 0.05$). In a third investigation, The K-SES measured before surgery was predictive of the Lysholm score ($P = 0.003$) and performance on a single-leg hop test ($P < 0.05$) 1 year after ACL reconstruction [59]. Ardern et al. [60] found significant differences in K-SES mean scores between patients who were satisfied, mostly satisfied, and dissatisfied (8.3, 6.9, and 4.8 points, respectively; $P < 0.001$) 3 years after ACL reconstruction.

Table 23.11 The knee self-efficacy scale [57]

A. Daily activities: how certain are you right now about
1. Walking in the forest
2. Climbing up and down a hill/stairs
3. Going out dancing
4. Jumping ashore from a boat
5. Running after small children
6. Running for the tram/bus
7. Working in the garden
B. Sports and leisure activities: how certain are you right now about
1. Cycling a long distance
2. Cross country skiing
3. Riding a horse
4. Swimming
5. Hiking in the mountains
C. Physical activities: how certain are you right now about
1. Squatting
2. Jumping sideways from one leg to the other
3. Working out hard a short time after the injury or surgery
4. Doing one-leg hops on the injured leg
5. Moving around in a rocking small boat
6. Doing fast twisting
D. Your knee function in the future: how certain are you that
1. You can return to the same physical activity level as before the injury?
2. You would not suffer any new injuries to your knee?
3. Your knee will not "break"?
4. Your knee will not get worse than before surgery?

All questions answered on an 11-grade Likert scale where 0 = not at all certain and 10 = very certain

23.3.4 Injury-Psychological Readiness to Return to Sport Scale (I-PRRS) [61]

Glazer [61] developed the Injury-Psychological Readiness to Return to Sport Scale (I-PRRS) (Table 23.12) and provided preliminary reliability and validity data from 22 injured collegiate athletes. Reliability measures were adequate (ICC 0.78–0.93 at 4 data-collection time points), as were content, concurrent, and external validity. Podlog et al. [62] reported acceptable reliability of a slightly modified version of the I-PRRS (ICC 0.90) in 118 injured high school athletes. The injuries varied in both of these studies and, as of the time of writing, this scale had not been used in ACL-injured or ACL-reconstructed cohorts.

23.3.5 Reinjury Anxiety Inventory (RIA) [63]

Walker et al. [63] developed the 28-item Reinjury Anxiety Inventory (RIA) shown in Table 23.13 to measure anxieties related to rehabilitation (RIA-R 15 items) and return to training or competition (RIA-RE 13 items). The questionnaire was completed by 248 athletes

Table 23.12 Injury-psychological readiness to return to sport scale [61]

Rate your confidence to return to your sport on a scale from 0 to 100
1. My overall confidence to play is _____
2. My confidence to play without pain is _____
3. My confidence to give 100% effort is _____
4. My confidence to not concentrate on the injury is _____
5. My confidence in the injured body part to handle the demands of the situation is _____
6. My confidence in my skill level/ability is _____

Total _____
Divide the total by 10 to calculate final score (maximum score = 60). A score of 60 implies the athlete has complete confidence to return to sport; 40, moderate confidence; and 20, low overall confidence

Table 23.13 Reinjury anxiety inventory [63]

	Not at all	Somewhat	Moderately so	Very much so
1. I am worried about becoming reinjured during rehabilitation	0	1	2	3
2. I am worried about becoming reinjured during re-entry into competition	0	1	2	3
3. I feel nervous about becoming reinjured during rehabilitation	0	1	2	3
4. I feel nervous about becoming reinjured during re-entry into competition	0	1	2	3
5. I have doubts that I will remain injury free during rehabilitation	0	1	2	3
6. I have doubts that I will remain injury free during re-entry into competition	0	1	2	3
7. I feel on edge about becoming reinjured during rehabilitation	0	1	2	3
8. I feel on edge about becoming reinjured during re-entry into competition	0	1	2	3
9. I am worried that I may not do as well as I could in rehabilitation due to reinjury worries	0	1	2	3
10. I am worried that I may not do as well as I could on returning to competition due to reinjury worries	0	1	2	3
11. My body feels tense about rehabilitation because of reinjury worries	0	1	2	3
12. My body feels tense about re-entering competition because of reinjury worries	0	1	2	3
13. I feel confident that I will not become reinjured during re-entry into competition	0	1	2	3
14. I am worried about failing during rehabilitation due to my reinjury worries	0	1	2	3
15. I am worried about failing when re-entering into competition due to reinjury worries	0	1	2	3
16. Reinjury worries about rehabilitation make my body feel tense	0	1	2	3
17. Reinjury worries about re-entry into competition make my body feel tense	0	1	2	3
18. I am worried about performing poorly during rehabilitation due to reinjury worries	0	1	2	3
19. I am worried about performing poorly during re-entry into competition due to reinjury worries	0	1	2	3
20. I am worried about failing to achieve full re-entry into competition due to reinjury worries	0	1	2	3
21. I feel my stomach sinking due to reinjury worries during rehabilitation	0	1	2	3
22. I am worried that others will be disappointed if I become reinjured during re-entry into competition	0	1	2	3
23. The thought of reinjury during re-entry into competition makes my palms sweaty	0	1	2	3
24. I am confident about not becoming reinjured during rehabilitation because I mentally picture myself staying injury free	0	1	2	3
25. I am worried about concentrating during rehabilitation because of reinjury worries	0	1	2	3
26. I am worried about concentrating during re-entry into a competition because of reinjury worries	0	1	2	3
27. My body feels tight due to reinjury worries during rehabilitation	0	1	2	3
28. My body feels tight due to reinjury worries during re-entry into competition	0	1	2	3

Scoring: rehabilitation reinjury anxiety (RIA-R)

Scores for items 1, 3, 5, 7, 9, 11, 14, 16, 18, 21, 24, 25, 27 are added to calculate an athlete's RIA-R (item 24 requires reverse scoring). A minimum score of 0 indicates a complete absence of RIA-R and a maximum score of 39 indicates that the athlete was extremely anxious about reinjury in rehabilitation

Re-entry into competition reinjury anxiety (RIA-RE)

Scores on items 2, 4, 6, 8, 10, 12, 13, 15, 17, 19, 20, 22, 23, 26, and 28 are added to calculate an athlete's RIA-RE (item 13 on this construct also requires reverse scoring). A minimum score of 0 indicates a complete absence of any RIA-RE and a maximum score of 45 indicates that the injured athlete was extremely anxious about reinjury in re-entry into training/competition who were undergoing treatment for a variety of injuries. The internal consistency for both RIA and RIA-R was determined using Cronbach's alpha in which 0.70 is considered the minimum for an adequate internally consistent scale. The study reported excellent internal consistency for RIA-R (α = 0.98) and RIA-RE (α = 0.96). Significant correlations were reported between RIA-R and RIA-RE constructs (range, 0.41–0.65, $P < 0.05$), which was interpreted as demonstrating that athletic injury causes reinjury anxieties both in rehabilitation and upon re-entering training or competition.

23.3.6 Quick Inventory of Depressive Symptomatology (QIDS) [64]

Rush et al. [64] developed the 16-item Quick Inventory of Depressive Symptomatology (QIDS, Table 23.14) from the 30-item Inventory of Depressive Symptomatology and evaluated its psychometric properties in a group of 596 adults with major depressive disorder. The internal consistency was high (α = 0.86) and the instrument was found to be sensitive to symptom change, indicating high concurrent validity. The researchers commented that it could be used as a simple screening tool in primary care. Trivedi et al. [65] evaluated the psychometric properties of the QIDS in 544 patients with major depressive disorder and 402 patients with bipolar disorder. Internal consistency was acceptable (α range, 0.86–0.94) and high concurrent validity was found in both groups of patients. Bernstein et al. [66] reported acceptable reliability of the QIDS in 140 adolescent patients with a wide range of depressive symptoms. Reilly et al. [67] conducted a systematic review on the psychometric properties of this instrument that included 37 studies with 17,118 participants. Internal consistency was adequate (α range, 0.65–0.87), concurrent validity was moderate or high with other commonly used depression scales, discriminant validity was validated, and responsiveness to change was acceptable.

Table 23.14 Quick inventory of depressive symptomatology [64]

1. Falling asleep
0 I never take longer than 30 min to fall asleep
1 I take at least 30 min to fall asleep, less than half the time
2 I take at least 30 min to fall asleep, more than half the time
3 I take more than 60 min to fall asleep, more than half the time
2. Sleep during the night
0 I do not wake up at night
1 I have a restless, light sleep with a few brief awakenings each night
2 I wake up at least once a night, but I go back to sleep easily
3 I awaken more than once a night and stay awake for 20 min or more, more than half the time
3. Waking up too early
0 Most of the time, I awaken no more than 30 min before I need to get up
1 More than half the time, I awaken more than 30 min before I need to get up
2 I almost always awaken at least 1 h or so before I need to, but I go back to sleep eventually
3 I awaken at least 1 h before I need to, and can't go back to sleep
4. Sleeping too much
0 I sleep no longer than 7–8 h/night, without napping during the day
1 I sleep no longer than 10 h in a 24-h period including naps
2 I sleep no longer than 12 h in a 24-h period including naps
3 I sleep longer than 12 h in a 24-h period including naps
5. Feeling sad
0 I do not feel sad
1 I feel sad less than half the time
2 I feel sad more than half the time
3 I feel sad nearly all of the time
6. Decreased appetite

(continued)

Table 23.14 (continued)

0 There is no change in my usual appetite
1 I eat somewhat less often or lesser amounts of food than usual
2 I eat much less than usual and only with personal effort
3 I rarely eat within a 24-h period, and only with extreme personal effort or when others persuade me to eat
7. Increased appetite
0 There is no change from my usual appetite
1 I feel a need to eat more frequently than usual
2 I regularly eat more often and/or greater amounts of food than usual
3 I feel the drive to overeat both at mealtime and between meals
8. Decreased weight (within the last 2 weeks)
0 I have not had a change in my weight
1 I feel as if I've had a slight weight loss
2 I have lost 2 pounds or more
3 I have lost 5 pounds or more
9. Increased weight (within the last 2 weeks)
0 I have not had a change in my weight
1 I feel as if I've had a slight weight gain
2 I have gained 2 pounds or more
3 I have gained 5 pounds or more
10. Concentration/decision making
0 There is no change in my usual capacity to concentrate or make decisions
1 I occasionally feel indecisive or find that my attention wanders
2 Most of the time, I struggle to focus my attention or to make decisions
3 I cannot concentrate well enough to read or cannot make even minor decisions
11. View of myself
0 I see myself as equally worthwhile and deserving as other people
1 I am more self-blaming than usual
2 I largely believe that I cause problems for others
3 I think almost constantly about major and minor defects in myself
12. Thoughts of death or suicide
0 I do not think of suicide or death
1 I feel that life is empty or wonder if it's worth living
2 I think of suicide or death several times a week for several minutes
3 I think of suicide or death several times a day in some detail, or I have made specific plans for suicide or have actually tried to take my life
13. General interest
0 There is no change from usual in how interested I am in other people or activities
1 I notice that I am less interested in people or activities
2 I find I have interest in only one or two of my formerly pursued activities
3 I have virtually no interest in formerly pursued activities
14. Energy level
0 There is no change in my usual level of energy
1 I get tired more easily than usual
2 I have to make a big effort to start finishing my usual daily activities (for example, shopping, homework, cooking or going to work)
3 I really cannot carry out most of my usual daily activities because I just don't have the energy
15. Feeling slowed down
0 I think, speak, and move at my usual rate of speed
1 I find that my thinking is slowed down or my voice sounds dull or flat
2 It takes me several seconds to respond to most questions and I'm sure my thinking is slowed
3 I am often unable to respond to questions without extreme effort
16. Feeling restless
0 I do not feel restless
1 I'm often fidgety, wringing my hands, or need to shift how I am sitting

(continued)

2 I have impulses to move about and am quite restless
3 At times, I am unable to stay seated and need to pace around
Scoring: (total score range, 0–27)
1. Highest score on sleep items (1–4) ____
2. Enter score on item 5 ____
3. Highest score on appetite/weight items (6–9) ____
4. Enter score on item 10 ____
5. Enter score on item 11 ____
6. Enter score on item 12 ____
7. Enter score on item 13 ____
8. Enter score on item 14 ____
9. Highest score on item 15 or 16 ____
10. Sum the item scores for a total score ____

General guidelines: score <5 no depression, 6–10 mild depression, 11–15 moderate depression, 16–20 severe depression, >20 very severe depression

23.3.7 Multidimensional Health Locus of Control Scale [68]

Wallston et al. developed the Multidimensional Health Locus of Control Scale (Table 23.15) in 1978 in order to determine if health-related behaviors are either primarily internal, a matter of chance, or under the control of powerful others. Individuals with an internal locus of control feel responsible and able to control their behaviors and resulting consequences, whereas those with an external locus of control believe their behaviors and resulting consequences are dictated by external forces or chance. Many studies [69–72] have investigated the psychometric properties of this scale, with adequate internal consistency (α range 0.70–0.87), reliability (R range 0.61–0.75, $P < 0.01$), construct validity, divergent validity, and convergent validity reported as summarized by Ross et al. [73].

23.3.8 State-Trait Anxiety Inventory [74]

The State-Trait Anxiety Inventory is a self-report measure that indicates the intensity of feelings of anxiety (Tables 23.16 and 23.17). Developed by Spielberger et al. [74], this instrument distinguishes between *state anxiety*, which is a temporary condition experienced in specific situations, and *trait anxiety*, which is a general tendency to perceive situations as threatening. Numerous studies have reported psychometric properties of this instrument, including high internal consistency (α ranges 0.81–0.94 state scale; 0.67–0.95 trait scale) and reliability (0.78–0.83 trait scale; 0.69–0.76 state scale), and adequate convergent validity [75]. A study in 1124 psychiatric patients and 877 healthy subjects found that this instrument measures general negative affect, including specific aspects of cognitive anxiety and depression together [76], and not the intensity of clinical anxiety per se.

23.4 Conclusions

There are several commonly used scales available to rate athletic activities that have been developed specifically for patients with knee injuries and disorders. It is important to understand the strengths and potential biases of these instruments as well as their reliability, validity, and responsiveness properties. In addition, several validated questionnaires are available that can help determine an athlete's psychological status. Psychological factors such as fear of reinjury, anxiety, depression, and preoperative stress are common barriers to RTS and overall patient satisfaction after serious knee injuries and operations. The selection of the appropriate instrument to use to rate either sports activity levels or psychological issues should be done with careful consideration of its psychometric properties.

Table 23.15 Multidimensional health locus of control scale (MHLC) [68]

Subscale	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
A: Internal					
If I get sick, it is my own behavior that determines how soon I get well	1	2	3	4	5
I am in control of my health	1	2	3	4	5
When I get sick, I am to blame	1	2	3	4	5
The main thing which affects my health is what I myself do	1	2	3	4	5
If I take care of myself, I can avoid illness	1	2	3	4	5
If I take the right actions, I can stay healthy	1	2	3	4	5
Total Score _____					
B. Powerful others					
Having regular contact with my physician is the best way for me to avoid illness	1	2	3	4	5
Whenever I don't feel well, I should consult a medically-trained professional	1	2	3	4	5
My family has a lot to do with my becoming sick or staying healthy	1	2	3	4	5
Health professionals control my health	1	2	3	4	5
When I recover from an illness, it's usually because other people (e.g., doctors,	1	2	3	4	5
nurses, family, and friends) have been taking good care of me	1	2	3	4	5
Regarding my health, I can only do what my doctor tells me to do					
Total Score _____					
C. Chance					
No matter what I do, if I am going to get sick, I will get sick	1	2	3	4	5
Most things that affect my health happen to me by accident	1	2	3	4	5
Luck plays a big part in determining how soon I will recover from an illness	1	2	3	4	5
My good health is largely a matter of good fortune	1	2	3	4	5
If it's meant to be, I will stay healthy	1	2	3	4	5
No matter what I do, I'm likely to get sick	1	2	3	4	5
Total Score _____					

Scoring: for each subscale, a score of 6–14 indicates low on that particular dimension, a score of 15–22 indicates moderate on that particular dimension; and a score of 23–30 indicates a strong inclination to that particular dimension

Table 23.16 State-trait anxiety inventory for Y-1 (state anxiety) [74]

	Not at all	Somewhat	Moderately so	Very much so
1. I feel calm	1	2	3	4
2. I feel secure	1	2	3	4
3. I am tense	1	2	3	4
4. I feel strained	1	2	3	4
5. I feel at ease	1	2	3	4
6. I feel upset	1	2	3	4
7. I am presently worrying over possible misfortunes	1	2	3	4
8. I feel satisfied	1	2	3	4
9. I feel frightened	1	2	3	4
10. I feel comfortable	1	2	3	4
11. I feel self-confident	1	2	3	4
12. I feel nervous	1	2	3	4
13. I am jittery	1	2	3	4
14. I feel indecisive	1	2	3	4
15. I am relaxed	1	2	3	4
16. I feel content	1	2	3	4
17. I am worried	1	2	3	4
18. I feel confused	1	2	3	4
19. I feel steady	1	2	3	4
20. I feel pleasant	1	2	3	4

Directions: A number of statements which people have used to describe themselves are given below. Read each statement and then circle the number that indicates how you feel right now, that is, at this moment. There are no right or wrong answers. Do not spend too much time on any one statement, but give the answer which seems to describe your present feelings best
Scoring available at www.mindgarden.com

Table 23.17 State-trait anxiety inventory for Y-2 (trait anxiety) [74]

State-Trait anxiety inventory for Y-2 (trait anxiety)	Almost never	Somewhat	Often	Almost always
1. I feel pleasant	1	2	3	4
2. I feel nervous and restless	1	2	3	4
3. I feel satisfied with myself	1	2	3	4
4. I wish I could be as happy as others seem to be	1	2	3	4
5. I feel like a failure	1	2	3	4
6. I feel rested	1	2	3	4
7. I am calm, cool, and collected	1	2	3	4
8. I feel that difficulties are piling up so that I cannot overcome them	1	2	3	4
9. I worry too much over something that doesn't matter	1	2	3	4
10. I am happy	1	2	3	4
11. I have disturbing thoughts	1	2	3	4
12. I lack self-confidence	1	2	3	4
13. I feel secure	1	2	3	4
14. I make decisions easily	1	2	3	4
15. I feel inadequate	1	2	3	4
16. I am content	1	2	3	4
17. Some unimportant thoughts run through my mind and bother me	1	2	3	4
18. I take disappointments so keenly that I can't put them out of my mind	1	2	3	4
19. I am a steady person	1	2	3	4
20. I get in a state of tension or turmoil as I think over my recent concerns and interests	1	2	3	4

Directions: A number of statements which people have used to describe themselves are given below. Read each statement and then circle the number that indicates how you generally feel. There are no right or wrong answers. Do not spend too much time on any one statement, but give the answer which seems to describe how you generally feel
Scoring available at www.mindgarden.com

References

1. Ardern CL, Taylor NF, Feller JA, Webster KE. Fear of re-injury in people who have returned to sport following anterior cruciate ligament reconstruction surgery. J Sci Med Sport. 2012;15(6):488–95. https://doi.org/10.1016/j.jsams.2012.03.015.
2. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2013;41(7):1549–58. https://doi.org/10.1177/0363546513489284.
3. Ardern CL, Osterberg A, Tagesson S, Gauffin H, Webster KE, Kvist J. The impact of psychological readiness to return to sport and recreational activities after anterior cruciate ligament reconstruction. Br J Sports Med. 2014;48(22):1613–9. https://doi.org/10.1136/bjsports-2014-093842.
4. Ardern CL. Anterior cruciate ligament reconstruction-not exactly a one-way ticket back to the preinjury level: a review of contextual factors affecting return to sport after surgery. Sports Health. 2015;7(3):224–30. https://doi.org/10.1177/1941738115578131.
5. Christino MA, Fantry AJ, Vopat BG. Psychological aspects of recovery following anterior cruciate ligament reconstruction. J Am Acad Orthop Surg. 2015;23(8):501–9. https://doi.org/10.5435/JAAOS-D-14-00173.
6. Everhart JS, Best TM, Flanigan DC. Psychological predictors of anterior cruciate ligament reconstruction outcomes: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2015;23(3):752–62. https://doi.org/10.1007/s00167-013-2699-1.
7. Flanigan DC, Everhart JS, Pedroza A, Smith T, Kaeding CC. Fear of reinjury (kinesiophobia) and persistent knee symptoms are common factors for lack of return to sport after anterior cruciate ligament reconstruction. Arthroscopy. 2013;29(8):1322–9. https://doi.org/10.1016/j.arthro.2013.05.015.
8. Hsu CJ, Meierbachtol A, George SZ, Chmielewski TL. Fear of reinjury in athletes. Sports Health. 2017;9(2):162–7. https://doi.org/10.1177/1941738116666813.
9. Lentz TA, Zeppieri G Jr, George SZ, Tillman SM, Moser MW, Farmer KW, Chmielewski TL. Comparison of physical impairment, functional, and psychosocial measures based on fear of reinjury/lack of confidence and return-to-sport status after ACL reconstruction. Am J Sports Med. 2015;43(2):345–53. https://doi.org/10.1177/0363546514559707.
10. Podlog L, Heil J, Schulte S. Psychosocial factors in sports injury rehabilitation and return to play. Phys Med Rehabil Clin N Am. 2014;25(4):915–30. https://doi.org/10.1016/j.pmr.2014.06.011.
11. Rosso F, Bonasia DE, Cottino U, Cambursano S, Dettoni F, Rossi R. Factors affecting subjective and objective outcomes and return to play in anterior cruciate ligament reconstruction: a retrospective cohort study. Joints. 2018;6(1):23–32. https://doi.org/10.1055/s-0038-1636931.
12. Sonesson S, Kvist J, Ardern C, Osterberg A, Silbernagel KG. Psychological factors are important to return to pre-injury sport activity after anterior cruciate ligament reconstruction: expect and motivate to satisfy. Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1375–84. https://doi.org/10.1007/s00167-016-4294-8.
13. Noyes FR, Barber SD, Mangine RE. Bone-patellar ligament-bone and fascia lata allografts for reconstruction of the anterior cruciate ligament. J Bone Joint Surg. 1990;72(8):1125–36.
14. Barber-Westin SD, Noyes FR, McCloskey JW. Rigorous statistical reliability, validity, and responsiveness testing of the Cincinnati knee rating system in 350 subjects with uninjured, injured, or anterior cruciate ligament-reconstructed knees. Am J Sports Med. 1999;27(4):402–16.
15. Marx RG, Jones EC, Allen AA, Altchek DW, O'Brien SJ, Rodeo SA, Williams RJ, Warren RF, Wickiewicz TL. Reliability, validity, and responsiveness of four knee outcome scales for athletic patients. J Bone Joint Surg. 2001;83-A(10):1459–69.
16. Greco NJ, Anderson AF, Mann BJ, Cole BJ, Farr J, Nissen CW, Irrgang JJ. Responsiveness of the International Knee Documentation Committee Subjective Knee form in comparison to the Western Ontario and McMaster Universities Osteoarthritis Index, modified Cincinnati knee rating system, and short form 36 in patients with focal articular cartilage defects. Am J Sports Med. 2010;38(5):891–902. https://doi.org/10.1177/0363546509354163.
17. Noyes FR, Barber SD, Mooar LA. A rationale for assessing sports activity levels and limitations in knee disorders. Clin Orthop Relat Res. 1989;246:238–49.
18. Hopper DM, Goh SC, Wentworth LA, Chan DYK, Chau JHW, Wootton GJ, Strauss GR, Boyle JJ. Test-retest reliability of knee rating scales and functional hop tests one year following anterior cruciate ligament reconstruction. Phys Ther Sport. 2002;3:10–8.
19. Letchford R, Sparkes V, van Deursen RW. Assessing participation in the ACL injured population: selecting a patient reported outcome measure on the basis of measurement properties. Knee. 2015;22(3):262–9. https://doi.org/10.1016/j.knee.2015.01.010.
20. Risberg MA, Holm I, Steen H, Beynnon BD. Sensitivity to changes over time for the IKDC form, the Lysholm score, and the Cincinnati knee score. A prospective study of 120 ACL reconstructed patients with a 2-year follow-up. Knee Surg Sports Traumatol Arthrosc. 1999;7:152–9.
21. Tegner Y, Lysholm J. Rating systems in the evaluation of knee ligament injuries. Clin Orthop Relat Res. 1985;198(198):43–9.
22. Briggs KK, Kocher MS, Rodkey WG, Steadman JR. Reliability, validity, and responsiveness of the Lysholm knee score and Tegner activity scale for patients with meniscal injury of the knee. J Bone Joint Surg. 2006;88(4):698–705.

23. Paxton EW, Fithian DC, Stone ML, Silva P. The reliability and validity of knee-specific and general health instruments in assessing acute patellar dislocation outcomes. Am J Sports Med. 2003;31(4):487–92.
24. Briggs KK, Lysholm J, Tegner Y, Rodkey WG, Kocher MS, Steadman JR. The reliability, validity, and responsiveness of the Lysholm score and Tegner activity scale for anterior cruciate ligament injuries of the knee: 25 years later. Am J Sports Med. 2009;37(5):890–7. https://doi.org/10.1177/0363546508330143.
25. Ebert JR, Smith A, Wood DJ, Ackland TR. A comparison of the responsiveness of 4 commonly used patient-reported outcome instruments at 5 years after matrix-induced autologous chondrocyte implantation. Am J Sports Med. 2013;41(12):2791–9. https://doi.org/10.1177/0363546513502314.
26. Naal FD, Impellizzeri FM, Leunig M. Which is the best activity rating scale for patients undergoing total joint arthroplasty? Clin Orthop Relat Res. 2009;467(4):958–65. https://doi.org/10.1007/s11999-008-0358-5.
27. Zahiri CA, Schmalzried TP, Szuszczewicz ES, Amstutz HC. Assessing activity in joint replacement patients. J Arthroplast. 1998;13(8):890–5.
28. Marx RG, Stump TJ, Jones EC, Wickiewicz TL, Warren RF. Development and evaluation of an activity rating scale for disorders of the knee. Am J Sports Med. 2001;29(2):213–8.
29. Craig CL, Marshall AL, Sjostrom M, Bauman AE, Booth ML, Ainsworth BE, Pratt M, Ekelund U, Yngve A, Sallis JF, Oja P. International physical activity questionnaire: 12-country reliability and validity. Med Sci Sports Exerc. 2003;35(8):1381–95. https://doi.org/10.1249/01.MSS.0000078924.61453.FB.
30. Hefti F, Muller W, Jakob RP, Staubli HU. Evaluation of knee ligament injuries with the IKDC form. Knee Surg Sports Traumatol Arthrosc. 1993;1(3-4):226–34.
31. Irrgang JJ, Anderson AF, Boland AL, Harner CD, Kurosaka M, Neyret P, Richmond JC, Shelborne KD. Development and validation of the international knee documentation committee subjective knee form. Am J Sports Med. 2001;29(5):600–13.
32. Irrgang JJ, Anderson AF, Boland AL, Harner CD, Neyret P, Richmond JC, Shelbourne KD. Responsiveness of the international knee documentation committee subjective knee form. Am J Sports Med. 2006;34(10):1567–73.
33. Webster KE, Feller JA, Lambros C. Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. Phys Ther Sport. 2008;9(1):9–15. https://doi.org/10.1016/j.ptsp.2007.09.003.
34. Jia ZY, Cui J, Wang W, Xue CC, Liu TZ, Huang X, Xu WD. Translation and validation of the simplified Chinese version of the anterior cruciate ligament-return to sport after injury (ACL-RSI). Knee Surg Sports Traumatol Arthrosc. 2018;26(10):2997–3003. https://doi.org/10.1007/s00167-018-4850-5.
35. Silva LO, Mendes LMR, Lima POP, Almeida GPL. Translation, cross-adaptation and measurement properties of the Brazilian version of the ACL-RSI Scale and ACL-QoL Questionnaire in patients with anterior cruciate ligament reconstruction. Braz J Phys Ther. 2018;22(2):127–34. https://doi.org/10.1016/j.bjpt.2017.09.006.
36. Harput G, Tok D, Ulusoy B, Eraslan L, Yildiz TI, Turgut E, Demirci S, Duzgun I, Tunay VB, Baltaci G, Ergun N. Translation and cross-cultural adaptation of the anterior cruciate ligament-return to sport after injury (ACL-RSI) scale into Turkish. Knee Surg Sports Traumatol Arthrosc. 2017;25(1):159–64. https://doi.org/10.1007/s00167-016-4288-6.
37. Slagers AJ, Reininga IH, van den Akker-Scheek I. The Dutch language anterior cruciate ligament return to sport after injury scale (ACL-RSI) - validity and reliability. J Sports Sci. 2017;35(4):393–401. https://doi.org/10.1080/02640414.2016.1167230.
38. Bohu Y, Klouche S, Lefevre N, Webster K, Herman S. Translation, cross-cultural adaptation and validation of the French version of the anterior cruciate ligament-return to sport after injury (ACL-RSI) scale. Knee Surg Sports Traumatol Arthrosc. 2015;23(4):1192–6. https://doi.org/10.1007/s00167-014-2942-4.
39. Kvist J, Osterberg A, Gauffin H, Tagesson S, Webster K, Ardern C. Translation and measurement properties of the Swedish version of ACL-return to sports after injury questionnaire. Scand J Med Sci Sports. 2013;23(5):568–75. https://doi.org/10.1111/j.1600-0838.2011.01438.x.
40. Webster KE, Feller JA. Development and validation of a short version of the anterior cruciate ligament return to sport after injury (ACL-RSI) scale. Orthop J Sports Med. 2018;6(4):2325967118763763. https://doi.org/10.1177/2325967118763763.
41. Kvist J, Ek A, Sporrstedt K, Good L. Fear of re-injury: a hindrance for returning to sports after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2005;13(5):393–7. https://doi.org/10.1007/s00167-004-0591-8.
42. Vlaeyen JW, Kole-Snijders AM, Boeren RG, van Eek H. Fear of movement/(re)injury in chronic low back pain and its relation to behavioral performance. Pain. 1995;62(3):363–72.
43. French DJ, France CR, Vigneau F, French JA, Evans RT. Fear of movement/(re)injury in chronic pain: a psychometric assessment of the original English version of the Tampa scale for kinesiophobia (TSK). Pain. 2007;127(1):42–51. https://doi.org/10.1016/j.pain.2006.07.016.
44. Lundberg MKE, Styf J, Carlsson SG. A psychometric evaluation of the Tampa Scale for Kinesiophobia — from a physiotherapeutic perspective. Physiother Theory Pract. 2004;20(2):121–33. https://doi.org/10.1080/09593980490453002.
45. Roelofs J, Goubert L, Peters ML, Vlaeyen J, Crombez G. The Tampa Scale for Kinesiophobia: further examination of psychometric properties in patients with chronic low back pain and fibromyalgia. Eur J

Pain. 2004;8(5):495–502. https://doi.org/10.1016/j.ejpain.2003.11.016.

46. Swinkels-Meewisse EJCM, Swinkels RAHM, Verbeek ALM, Vlaeyen JWS, Oostendorp RAB. Psychometric properties of the Tampa Scale for kinesiophobia and the fear-avoidance beliefs questionnaire in acute low back pain. Man Ther. 2003;8(1):29–36. https://doi.org/10.1054/math.2002.0484.
47. Woby SR, Roach NK, Urmston M, Watson PJ. Psychometric properties of the TSK-11: a shortened version of the Tampa Scale for Kinesiophobia. Pain. 2005;117(1-2):137–44. https://doi.org/10.1016/j.pain.2005.05.029.
48. Tkachuk GA, Harris CA. Psychometric properties of the Tampa Scale for Kinesiophobia-11 (TSK-11). J Pain. 2012;13(10):970–7. https://doi.org/10.1016/j.jpain.2012.07.001.
49. de Souza FS, da Silva Marinho C, Siqueira FB, Maher CG, Costa LOP. Psychometric testing confirms that the Brazilian-Portuguese adaptations, the original versions of the fear-avoidance beliefs questionnaire, and the Tampa Scale of Kinesiophobia have similar measurement properties. Spine. 2008;33(9):1028–33. https://doi.org/10.1097/BRS.0b013e31816c8329.
50. Bunketorp L, Carlsson J, Kowalski J, Stener-Victorin E. Evaluating the reliability of multi-item scales: a non-parametric approach to the ordered categorical structure of data collected with the Swedish version of the Tampa Scale for Kinesiophobia and the self-efficacy scale. J Rehabil Med. 2005;37(5):330.
51. Gómez-Pérez L, López-Martínez AE, Ruiz-Párraga GT. Psychometric properties of the Spanish version of the Tampa Scale for Kinesiophobia (TSK). J Pain. 2010;12(4):425–35. https://doi.org/10.1016/j.jpain.2010.08.004.
52. Haugen AJ, Grøvle L, Keller A, Grotle M. Cross-cultural adaptation and validation of the Norwegian version of the Tampa Scale for Kinesiophobia. Spine. 2008;33(17):E595–601. https://doi.org/10.1097/BRS.0b013e31817c6c4b.
53. Rusu AC, Kreddig N, Hallner D, Hülsebusch J, Hasenbring MI. Fear of movement/(re)injury in low back pain: confirmatory validation of a German version of the Tampa Scale for Kinesiophobia. BMC Musculoskelet Disord. 2014;15(1):280. https://doi.org/10.1186/1471-2474-15-280.
54. Wong WS, Kwok HY, Luk KD, Chow YF, Mak KH, Tam BK, Wong ET, Fielding R. Fear of movement/(re)injury in Chinese patients with chronic pain: factorial validity of the Chinese version of the Tampa Scale for Kinesiophobia. J Rehabil Med. 2010;42(7):620–9.
55. Askary-Ashtiani A, Ebrahimi-Takamejani I, Torkaman G, Amiri M, Mousavi SJ. Reliability and validity of the Persian versions of the fear avoidance beliefs questionnaire and Tampa Scale of Kinesiophobia in patients with neck pain. Spine. 2014;39(18):E1095–102.
56. Monticone M, Giorgi I, Baiardi P, Barbieri M, Rocca B, Bonezzi C. Development of the Italian version of the Tampa Scale of Kinesiophobia (TSK-I): cross-cultural adaptation, factor analysis, reliability, and validity. Spine. 2010;35(12):1241–6. https://doi.org/10.1097/BRS.0b013e3181bfcbf6.
57. Thomee P, Wahrborg P, Borjesson M, Thomee R, Eriksson BI, Karlsson J. A new instrument for measuring self-efficacy in patients with an anterior cruciate ligament injury. Scand J Med Sci Sports. 2006;16(3):181–7.
58. Thomee P, Wahrborg P, Borjesson M, Thomee R, Eriksson BI, Karlsson J. Self-efficacy, symptoms and physical activity in patients with an anterior cruciate ligament injury: a prospective study. Scand J Med Sci Sports. 2007;17(3):238–45. https://doi.org/10.1111/j.1600-0838.2006.00557.x.
59. Thomee P, Wahrborg P, Borjesson M, Thomee R, Eriksson BI, Karlsson J. Self-efficacy of knee function as a pre-operative predictor of outcome 1 year after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2008;16(2):118–27. https://doi.org/10.1007/s00167-007-0433-6.
60. Ardern CL, Osterberg A, Sonesson S, Gauffin H, Webster KE, Kvist J. Satisfaction with knee function after primary anterior cruciate ligament reconstruction is associated with self-efficacy, quality of life, and returning to the preinjury physical activity. Arthroscopy. 2016;32(8):1631–1638.e1633. https://doi.org/10.1016/j.arthro.2016.01.035.
61. Glazer DD. Development and preliminary validation of the injury-psychological readiness to return to sport (I-PRRS) scale. J Athl Train. 2009;44(2):185–9. https://doi.org/10.4085/1062-6050-44.2.185.
62. Podlog L, Gao Z, Kenow L, Kleinert J, Granquist M, Newton M, Hannon J. Injury rehabilitation overadherence: preliminary scale validation and relationships with athletic identity and self-presentation concerns. J Athl Train. 2013;48(3):372–81. https://doi.org/10.4085/1062-6050-48.2.20.
63. Walker N, Thatcher J, Lavallee D. A preliminary development of the Re-Injury Anxiety Inventory (RIAI). Phys Ther Sport. 2010;11(1):23–9. https://doi.org/10.1016/j.ptsp.2009.09.003.
64. Rush AJ, Trivedi MH, Ibrahim HM, Carmody TJ, Arnow B, Klein DN, Markowitz JC, Ninan PT, Kornstein S, Manber R, Thase ME, Kocsis JH, Keller MB. The 16-item quick inventory of depressive symptomatology (QIDS), clinician rating (QIDS-C), and self-report (QIDS-SR): a psychometric evaluation in patients with chronic major depression. Biol Psychiatry. 2003;54(5):573–83.
65. Trivedi MH, Rush AJ, Ibrahim HM, Carmody TJ, Biggs MM, Suppes T, Crismon ML, Shores-Wilson K, Toprac MG, Dennehy EB, Witte B, Kashner TM. The inventory of depressive symptomatology, clinician rating (IDS-C) and self-report (IDS-SR), and the quick inventory of depressive symptomatology, clinician rating (QIDS-C) and self-report (QIDS-SR) in public sector patients with mood disorders: a psychometric evaluation. Psychol Med. 2004;34(1):73–82.

66. Bernstein IH, Rush AJ, Trivedi MH, Hughes CW, Macleod L, Witte BP, Jain S, Mayes TL, Emslie GJ. Psychometric properties of the quick inventory of depressive symptomatology in adolescents. Int J Methods Psychiatr Res. 2010;19(4):185–94. https://doi.org/10.1002/mpr.321.
67. Reilly TJ, MacGillivray SA, Reid IC, Cameron IM. Psychometric properties of the 16-item quick inventory of depressive symptomatology: a systematic review and meta-analysis. J Psychiatr Res. 2015;60:132–40. https://doi.org/10.1016/j.jpsychires.2014.09.008.
68. Wallston KA, Stein MJ, Smith CA. Form C of the MHLC scales: a condition-specific measure of locus of control. J Pers Assess. 1994;63(3):534–53. https://doi.org/10.1207/s15327752jpa6303_10.
69. Castarlenas E, Sole E, Racine M, Sanchez-Rodriguez E, Jensen MP, Miro J. Locus of control and pain: validity of the form C of the multidimensional health locus of control scales when used with adolescents. J Health Psychol. 2016;23(14):1853–62. https://doi.org/10.1177/1359105316669860.
70. Baken D, Stephens C. More dimensions for the multidimensional health locus of control: confirmatory factor analysis of competing models of the structure of control beliefs. J Health Psychol. 2005;10(5):643–56. https://doi.org/10.1177/1359105305055310.
71. Hubley AM, Wagner S. Using alternative forms of the multidimensional health locus of control scale: caveat emptor. Soc Indic Res. 2004;65:167–86.
72. Wallston KA. The validity of the multidimensional health locus of control scales. J Health Psychol. 2005;10(5):623–31. https://doi.org/10.1177/1359105305055304.
73. Ross TP, Ross LT, Short SD, Cataldo S. The multidimensional health locus of control scale: psychometric properties and form equivalence. Psychol Rep. 2015;116(3):889–913. https://doi.org/10.2466/09.02.PR0.116k29w3.
74. Spielberger C, Gorsuch R, Lushene R, Vagg P, Jacobs G. Manual for the state-trait anxiety inventory. Palo Alto: Consulting Psychologists Press; 1983.
75. McDowell I. Measuring health: a guide to rating scales and questionnaires. 3rd ed. New York: Oxford University Press; 2006.
76. Balsamo M, Romanelli R, Innamorati M, Ciccarese G, Carlucci L, Saggino A. The state-trait anxiety inventory: shadows and lights on its construct validity. J Psychopathol Behav Assess. 2013;35(1):475–86. https://doi.org/10.1007/s10862-013-9354-5.
77. Noyes FR, Barber-Westin SD. A comparison of results in acute and chronic anterior cruciate ligament ruptures of arthroscopically assisted autogenous patellar tendon reconstruction. Am J Sports Med. 1997;25(4):460–71.
78. Murphy GC, Foreman PE, Simpson CA, Molloy GN, Molloy EK. The development of a locus of control measure predictive of injured athletes' adherence to treatment. J Sci Med Sport. 1999;2(2):145–52.

24 Identification and Management of Psychosocial Issues in the Athlete for Return to Sport

Rogelio A. Coronado, Simone Herzberg, and Kristin R. Archer

24.1 Introduction

Psychosocial factors impact return to sport after anterior cruciate ligament reconstruction (ACLR) [1–3]. It is well known that after a sport injury, athletes experience a range of psychosocial disturbances including depressed mood, anxiety, social isolation, and a challenge to their athletic identity [4–7]. These cognitive and emotional states generally improve alongside physical functioning after surgery and postoperative rehabilitation [5, 7–10]. However, despite successful surgical repair and functional recovery, approximately half of athletes who undergo ACLR do not return to their sport post-recovery [11, 12]. Psychosocial factors are implicated as key variables explaining the discrepancy in functional recovery and the athlete's decision to return to sport after ACLR. To enhance return to sport outcomes, postoperative rehabilitation approaches should incorporate strategies that target both physical and psychosocial factors.

This chapter highlights key psychosocial factors involved in impacting return to sport after ACLR. Emphasis is placed on modifiable psychosocial characteristics that, if addressed, may improve the likelihood of return to sport. Additionally, psychosocial management strategies are discussed as possible therapeutic options for the athlete aiming to return to sport.

24.2 Psychosocial Models for Return to Sport

Conceptual models have been developed and adapted to depict the psychosocial factors relevant to recovery and return to sport. Current multidimensional biopsychosocial models highlight a range of influences including personal and situational factors [13–16]. For example, Ardern et al. [17] presented an adapted biopsychosocial model for return to sport that acknowledges contributions from the athlete's injury characteristics and sociodemographic, physical, psychological, and social/contextual variables. Currently, there is no universally accepted psychosocial model of return to sport after ACLR.

Wiese-Bjornstal et al. [14] outlined an integrated model of psychosocial responses after sports injury that impact recovery. In this model, domains of cognition (i.e., conscious appraisals regarding

R. A. Coronado · S. Herzberg
Department of Orthopaedic Surgery, Vanderbilt University Medical Center, Nashville, TN, USA
e-mail: rogelio.coronado@vumc.org; simone.d.herzberg@vanderbilt.edu

K. R. Archer (✉)
Department of Orthopaedic Surgery, Vanderbilt University Medical Center, Nashville, TN, USA

Department of Physical Medicine and Rehabilitation, Vanderbilt University Medical Center, Nashville, TN, USA
e-mail: kristin.archer@vumc.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_24

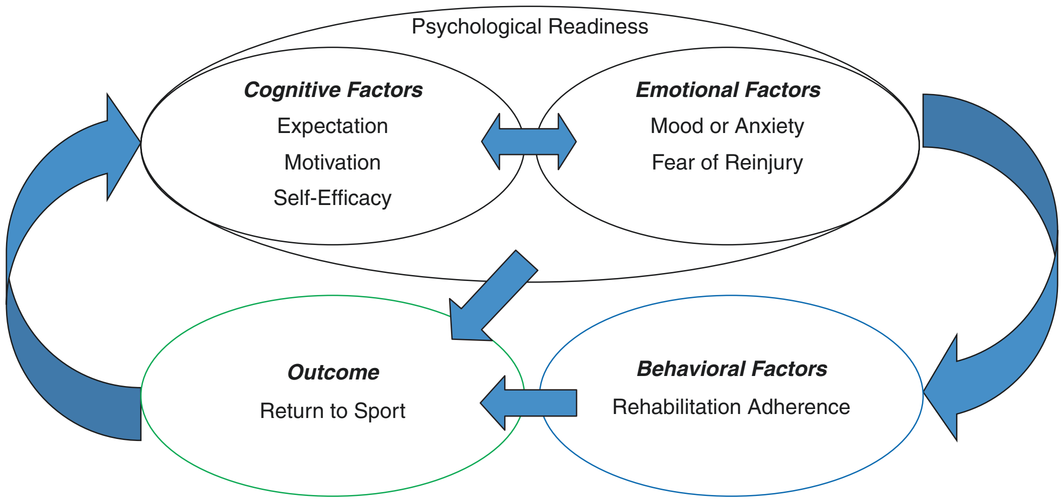


Fig. 24.1 Adapted conceptual psychosocial model for return to sport after anterior cruciate ligament reconstruction [14]

injury), affect (i.e., emotions and feelings), and behavior (i.e., athlete's effort and actions) interact in determining outcomes. Burland et al. [18] conducted a qualitative investigation of athlete's decisions to return to sport after ACLR and found key themes that fit within this integrated model. These themes relate to psychosocial constructs such as expectation, motivation, confidence, anxiety, and fear. Everhart et al. [19] introduced conceptual models focused specifically on self-efficacy, fear-avoidance, and social support. These models lean on previously derived psychological models and are adapted within the context of ACLR.

In this chapter, we use an adapted conceptual model (Fig. 24.1) based on the model by Wiese-Bjornstal et al. [14] that highlights the dynamic role of cognitive, emotional, and behavioral domains. The psychosocial factors that fit within these three constructs are informed from models that are relevant to post-ACLR return to sport by Everhart et al. [19] and Ardern et al. [17].

24.3 Cognitive Factors

24.3.1 Expectation of Recovery

Expectation pertains to an athlete's belief in what will occur after injury. Expectations can be related to anticipated outcomes after surgery, with one study finding that preoperative expectations about the length of recovery time is associated with returning to preinjury level of sport participation at 1 year after ACLR [20]. In this study, the more time an athlete estimated before returning to preinjury level, the lower the chance they returned to sport at 12 months [20]. In a qualitative study of athletes 1-year post-ACLR, Burland et al. [18] found that expectations about recovery played a major role in shaping athlete's decision to return to sport. Most athletes have high expectations about recovery and return to preinjury sport [21, 22]; however, initial expectations can be shaped by unrealistic goals or misinformation about the recovery process [23]. Many athletes may be unprepared for the lengthy and intensive course of postoperative rehabilitation [23–25]. Feucht et al. [22] reported that 94% of athletes with primary ACLR and 84% of athletes with revision ACLR expect to return to sport at the same preinjury level. This contrasts with the observed proportion of athletes reported in the literature (e.g., 44–55%) who attain this goal after ACLR [11, 12]. These studies underscore the importance of optimal preoperative education for establishing reasonable expectations of outcome.

24.3.2 Motivation to Return to Sport

Motivation to return to preinjury sport is another key factor in an athlete's decision regarding post-ACLR sport performance [3]. Gobbi and Francisco [26] found that participants who returned to sport following ACLR scored higher on the Psychovitality Questionnaire (Table 24.1),

Table 24.1 Selected psychosocial measures relevant to return to sport after anterior cruciate ligament reconstruction

Measure	Psychosocial construct(s)	Description
Anterior Cruciate Ligament—Return to Sport After Injury Scale (ACL-RSI) [27]	Psychological readiness to return to sport	The ACL-RSI is a 12-item questionnaire. Athletes respond to each question with a response ranging from "extremely" to "not at all." The original questionnaire used a 10-cm Visual Analog Scale, while modified versions have used Likert scales. Item responses are averaged for a score ranging from 1 to 10. Higher ACL-RSI scores indicate greater psychological readiness to return to sport
Emotional Responses of Athletes to Injury Questionnaire (ERAIQ) [5, 28]	Emotional response following injury	The ERAIQ is a 24-item questionnaire. Athletes respond to open-ended questions with single phrase answers, as well as list items in order of importance and rank emotions on a scale of 0 ("low") to 10 ("high"). Higher ERAIQ scores indicate greater emotional response as well as provide qualitative descriptions of the emotional response
Knee Self-Efficacy Scale (K-SES) [29]	Self-efficacy for knee function	The K-SES is a 22-item questionnaire that contains subscales for daily activities, sports activities, knee function tasks, and knee function in the future. Athletes respond to each question with a response ranging from 0 ("not at all certain") to 10 ("very certain"). Item responses are summed and divided by the number of items completed. Higher K-SES scores indicate greater self-efficacy for knee function
Psychovitality Questionnaire [26]	Motivation for return to sport	The Psychovitality questionnaire is a six-item questionnaire. Athletes respond to each question with a response of "not important," "slightly important," or "very important." Item responses are summed for a total ranging from 3 to 18. Higher Psychovitality scores indicate greater motivation for return to sport
Self-Efficacy for Rehabilitation Outcome Scale (SER) [8, 30]	Self-efficacy for performing behaviors related to physical rehabilitation	The SER is a 10-item questionnaire that has been modified from the original 12-item version. Athletes respond to each question with a response from 0 ("I cannot do it") to 10 ("certain I can do it"). Item responses are summed for a total ranging from 0 to 100. Higher SER scores indicate greater self-efficacy for performing behaviors related to physical rehabilitation
Tampa Scale of Kinesiophobia (TSK) [31, 32]	Fear of movement or reinjury	The TSK is an 11-item questionnaire. Athletes respond to each question with a response from 1 ("strongly disagree") to 4 ("strongly agree"). Item responses are summed for a total ranging from 11 to 44. Higher TSK scores indicate greater fear of movement or reinjury

a measure containing motivation-related questions, than participants who did not return to sport. In a cross-sectional study of female soccer players [33], motivation (measured by questions: "How important was it for you to return to your previous activity level?" and "Did you think it was possible for you to return to your previous activity level?") was associated with return to sport. Sonesson et al. [21] conducted a prospective study with 1-year follow-up in 65 athletes and found that athletes who returned to their preinjury sport had higher motivation, both preoperatively and during rehabilitation, than those who did not return to sport.

Motivation can also impact an athlete's compliance with rehabilitation and rehabilitation effort [34]. DiSanti et al. [35] found that athletes undergoing standard post-ACLR rehabilitation were often frustrated with basic exercises and exhibited low motivation during physical therapy. These findings suggest that motivational strategies during rehabilitation may help to increase compliance and the rate of successful return to sport.

24.3.3 Self-Efficacy

Self-efficacy has been studied within the context of recovery after ACLR as an athlete's judgment of their ability to carry out a task independently [36]. Preoperative self-efficacy in performing knee activities (measured by the Knee Self-Efficacy Scale, Table 24.1) has been shown to be predictive of return to sport 1 year after ACLR [37]. Hamrin Senorski et al. [38] observed a positive correlation between knee self-efficacy and return to sport in athletes who returned to knee-strenuous sports 10 months after ACLR compared to individuals who did not. Knee self-efficacy could be impacted by athlete's perceptions about their postoperative knee function. For example, lack of confidence in the postoperative knee has been found to impact activity engagement, return to sport, and performance [18]. Participation in rehabilitation and gradual progression to preinjury activities has the potential to increase knee self-efficacy [24].

Self-efficacy for rehabilitation (measured by Self-Efficacy for Rehabilitation Outcome Scale, Table 24.1) relates to an athlete's beliefs about participation in rehabilitation. Chmielewski et al. [8] examined self-efficacy for rehabilitation and found that early improvements in self-efficacy during the first 12 weeks of rehabilitation after ACLR were associated with early improvements in pain and function. These early adaptations may be beneficial for advancing through rehabilitation in preparation for return to sport [39].

24.4 Emotional Factors

24.4.1 Mood and Anxiety

Emotional factors such as mood, anxiety, and anger have been shown to impact knee function and quality of life [40]. Feelings of hopelessness and depression are common among athletes following ACLR and are associated with worse postoperative outcomes and decreased rates of return to sport [19, 41]. Tripp et al. [42] found that confidence in returning to sport was significantly reduced in those experiencing negative affect. Additionally, an athlete's desire to return to sport may be influenced by anxiety related to the level of athletic performance they can attain, the ongoing skill progression of other athletes, and their perception of reinjury [43].

Given the direct impact of mood and anxiety on return to sport, actions taken to promote healthy emotional responses (measured by the Emotional Responses of Athletes to Injury Questionnaire, Table 24.1) during rehabilitation may dramatically improve return to sport. Appropriate social support and encouragement can promote a positive experience for the injured athlete [18, 44]. Positive peer role models—athletes after ACLR at different rehabilitation stages—have been identified as facilitators of postoperative resilience [35]. Teammates, coaches, trainers, and family members can also be a source of positive interactions that can counteract negative feelings athletes may be experiencing [44, 45].

24.4.2 Fear of Movement or Reinjury

Fear of movement or reinjury (commonly measured with the Tampa Scale of Kinesiophobia, Table 24.1) is a primary reason for not returning to sport in up to 50% of athletes [42, 46–49]. A meta-analysis of studies on return to sport outcomes after ACLR found that fear of reinjury is the most commonly cited reason affecting postoperative sports participation [11]. Moreover, despite improvement during the early and middle phases of rehabilitation, fear can continue to increase as athletes approach the time to return to sport participation [5]. Ardern et al. [50] and Kvist et al. [51] found athletes who returned to their preinjury sport or activity level after ACLR exhibited less fear of reinjury than those who had not returned to their preinjury level. In a meta-analysis of data from six studies, Ardern [2] reported that lower fear of reinjury has a moderately large effect (pooled standardized mean difference = 0.7) on return to preinjury sport.

Fear of movement or reinjury can impact post-ACLR rehabilitation engagement, physical activity level, and/or progression to more advanced sport-specific strategies [39, 52, 53]. Chmielewski and George [39] reported that elevated fear of reinjury at 4 weeks after surgery was a modifiable risk factor predictive of an athlete's readiness for advanced rehabilitation at 12 weeks. Fear can impact some athletes' physical abilities through a heightened awareness or feeling of self-consciousness of their knee [18]. Common perceptions stemming from fear include the uncertainty of whether the knee is stable or reliable and hesitation with certain movements. There is preliminary evidence from a small cohort study of 40 athletes suggesting that higher levels of fear may place athletes at risk for a second ACL injury [54]. In this study, the 15 (38%) athletes who experienced a second ACL injury within 24 months after returning to sport had significantly higher levels of fear than the group who did not reinjure [54].

24.5 Psychological Readiness

Psychological readiness to return to sport is a multidimensional construct that encompasses an athlete's emotions, confidence, and risk appraisal related to returning to sport after ACLR. Podlog et al. [55] identified key attributes related to psychological readiness, including confidence in return to sport, realistic expectations of sporting abilities, and motivation to regain prior performance standards. Psychological readiness to return to sport can be assessed using the Anterior Cruciate Ligament—Return to Sport after Injury (ACL-RSI, Table 24.1) Scale [27].

There is considerable evidence supporting psychological readiness as an important prognostic factor for returning to sport after ACLR [1, 2, 10, 48, 56]. Ardern [2] reported that greater psychological readiness has a large effect (pooled standardized mean difference = 0.9) on return to preinjury sport. A cutoff score of 56 points on the ACL-RSI at 4 months after ACLR has been reported as having the best predictive value (sensitivity = 0.58; specificity = 0.83) for return to preinjury sport at 7 months [20]. Athletes with a score <56 may be at increased risk for not returning to their preinjury level [20].

24.6 Behavioral Factors

24.6.1 Rehabilitation Adherence

Rehabilitation adherence during the post-ACLR recovery phase can impact return to sport, with studies finding that moderate to full compliance with postoperative rehabilitation regimens is a significant predictor of both knee function and return to sport [56, 57]. Individuals that are fully compliant with rehabilitation have higher odds of successfully returning to sport when compared to non-compliant individuals [57]. There are a multitude of factors that have been found to influence rehabilitation adherence, including sport-specific factors, psychosocial characteristics, and situational factors [58–60]. Age may influence the primary factors driving rehabilitation adherence. For example, rehabilitation adherence of younger athletes relates more strongly to identity, whereas adherence in adolescents and young adults is associated with motivation and social support [61].

Rehabilitation strategies may increase adherence and, in turn, enhance recovery. Chan et al. [62] found that physical therapists' autonomy-supportive behaviors, which consist of encouraging value of results as opposed to reward or external motivation, can influence rehabilitation adherence through an athlete's autonomous motivation. These findings suggest that a rehabilitation approach that places emphasis on intrinsic motivation can increase an athlete's motivation to stay engaged with rehabilitation.

24.7 Management Strategies for Addressing Psychosocial Factors

Psychosocial determinants are integral in an athlete's decision-making process to return to sport. Despite this, traditional postoperative rehabilitation is almost exclusively focused on physical recovery. Moreover, a lack of consensus regarding optimal rehabilitation protocols and universally accepted criteria for return to sport have led to varying levels of physical and psychological readiness once an athlete is cleared for sport participation [63–65]. Given the link between psychosocial factors and return to sport, there have been recommendations for multimodal, "psychologically informed" approaches that combine traditional physical and sport-specific rehabilitation with psychosocial strategies [66].

24.7.1 Psychosocial Strategies from Randomized Trials

A systematic review by Coronado et al. [67] on psychosocial interventions for patients after ACLR found four randomized trials (*N* = 210) that examined the benefits of guided imagery and relaxation [68, 69], coping modeling [70], and visual imagery [71] (Table 24.2). The psychosocial strategies included in these trials were

Table 24.2 Description of psychosocial interventions used after anterior cruciate ligament reconstruction

Study	Design	Intervention	Psychological factor targeted	Psychological intervention components
Cupal and Brewer [68]	Randomized trial	Relaxation and guided imagery	Anxiety	Breath-assisted relaxation Imagery and mental rehearsals
Maddison et al. [69]	Randomized trial	Relaxation and guided imagery	Self-efficacy	Breath-assisted relaxation Imagery and mental rehearsals
Maddison et al. [70]	Randomized trial	Modeling videos	Anxiety Self-efficacy	Viewing models performing various tasks and exercises Listening to models expressing their initial expectations, perceptions of recovery, and challenges and experiences with their injury, surgery, and rehabilitation
Zaffagnini et al. [71]	Randomized trial	Therapeutic insight videos	Fear of movement or reinjury	Viewing psychological-enhancing videos that aim to elicit positive and therapeutic insight
Rock and Jones [72]	Case series	Counseling skills	Mood Rehabilitation adherence Social support	Active listening Action planning Challenging negative beliefs Coping strategies
McArdle [73]	Case study	Cognitive-behavioral therapy	Anger Fear of movement or reinjury Stress	Coping strategies Graded activity (desensitization) Informal modeling Time projection (imagery)
Mahoney and Hanrahan [74]	Case series	Acceptance and commitment therapy	Psychological flexibility	Cognitive defusion Experiential acceptance Mindfulness Self as context Values Committed action

implemented during standard postoperative ACLR rehabilitation. Guided imagery, or the process of mental rehearsal of activity and sport-specific skills, along with breath-assisted relaxation was found to be helpful in improving knee strength and decreasing reinjury anxiety and pain in one study [68], while another study [69] found improvement in knee laxity and a reduction in stress levels. Maddison et al. [70] found that the use of coping modeling, wherein patients watch videos of individuals performing specific tasks and rehabilitation exercises appropriate for the first 6 weeks after ACLR, was effective for improving short-term rehabilitation self-efficacy and patient-reported function. Visual imagery, in the form of art videos that were chosen to produce therapeutic insight into the psychological experience of recovery from surgery, was also found by Zaffagnini et al. [71] to improve short-term function in patients following ACLR.

24.7.2 Psychosocial Strategies from Case Studies

Case studies in patients post-ACLR have explored the benefits of counseling [72], cognitive-behavioral therapy [73], and acceptance and commitment therapy [74] (Table 24.2). Counseling skills, such as active listening and reflection, may provide emotional and social support that subsequently improves mood, rehabilitation adherence, and pain. Rock and Jones [72] reported that counseling skills may be particularly useful for patients that encounter setbacks in their rehabilitation following ACLR. Cognitive-behavioral therapy is a well-established non-pharmacologic treatment approach for addressing psychological distress and persistent pain conditions [75]. Specific types of cognitive-behavioral strategies that are relevant for patients following ACLR include personal coping skills, graded activity, and cognitive restructuring (identifying negative thoughts and replacing with positive ones). These strategies may be potentially beneficial for patients following ACLR who have high levels of anxiety, anger, and fear of reinjury as well as a high athletic identity [74, 76]. Finally, acceptance and commitment therapy (ACT) targets psychological flexibility through cognitive defusion (e.g., moving away from thoughts focused on fear of reinjury), acceptance, mindfulness (focusing on the present), value-driven behavior, and committed action. Mahoney and Hanrahan [74] suggest that ACT-based programs that include mindfulness and acceptance strategies may be effective for addressing emotions and emotion-driven behaviors that athletes are unwilling to accept during the postoperative recovery process.

24.7.3 Other Psychosocial Strategies

Additional psychosocial strategies that may be important to consider in future research include motivational imagery [77] and social support [78]. Motivational imagery focuses on achieving a specific goal, such as winning a game and/or on the emotions that arise from achieving the goal. While motivational imagery is used most often by athletes during competition, this technique may be helpful in increasing self-efficacy, decreasing anxiety, and motivating injured athletes prior to return to sport. Sordoni et al. [77] reported that athletes rarely transfer motivational imagery skills to injury rehabilitation; thus, research is needed to determine whether motivational imagery can facilitate recovery and return to sport following ACLR. Integrating social support into ACLR rehabilitation programs may also have the potential to improve recovery and return to sport. Scott et al. [24] and Johnson et al. [44] found that a strong support system and rich interaction with significant others were core themes that helped individuals cope successfully with recovery following ACLR. These social support systems can consist of family, friends, coaches, trainers, and athletes with a similar injury. In addition, social support strategies such as encouraging athletes to interact with team members during practice, games, and social events, even though injured, and participating in group rehabilitation sessions or home exercise programs may be areas for future prospective research. Meierbachtol et al. [78] found in a retrospective cohort study that advanced group training after ACLR was associated with improved psychological and functional outcomes post-training.

24.8 Future Directions for Research

There are several gaps in knowledge relating to psychosocial assessment and management after ACLR. First, there is limited evidence on optimal psychosocial screening in order to identify patients at risk for not returning to sport or not returning to full preinjury participation. For example, cutoff scores on well-established psychosocial measures would help rehabilitation providers implement targeted psychosocial interventions along with standard physical rehabilitation strategies.

Second, studies have not systematically studied psychosocial risk factors across the continuum of care (preoperative–postoperative rehabilitation—long-term follow-up). Many of the studies described in this chapter are qualitative investigations or cross-sectional designs that survey athletes from months to years after ACLR surgery.

Third, while psychosocial interventions have been studied in relation to psychosocial and patient-reported functional outcomes, no randomized clinical trial, to date, has examined the efficacy of a psychosocial program for returning athletes to preinjury sport post-ACLR. Additional systematic work is needed to better understand the contribution imagery, coping modeling, counseling, cognitive-behavioral therapy, ACT-based strategies, and social support can have when integrated within standard rehabilitation practice.

Finally, research is needed to better understand how expectations of recovery influence return to sport outcomes and how best to manage expectations before surgery and throughout the recovery period.

24.9 Conclusion

The goal of rehabilitation is to return athletes to their desired level of sport post-injury. And yet, despite improvements in surgical techniques and evidence-based physical rehabilitation protocols, only about one in two athletes will return to sport following ACLR [12]. An overwhelming body of research suggests that the decision to return to sport following ACLR is heavily influenced by psychosocial factors throughout recovery. These factors encompass cognitive (expectation, motivation, self-efficacy), emotional (mood and anxiety, fear of movement, or reinjury), and behavioral (rehabilitation adherence) domains.

Despite growing awareness of the impact of psychosocial effects on return to sport, traditional rehabilitation procedures and criteria for clearance to sport is centered almost exclusively on physical recovery. Rehabilitation protocols that combine physical and sport-centered rehabilitation techniques and psychosocial management strategies, such as imagery and relaxation, counseling/behavioral therapy, social support, and specific goal setting, have been suggested as possible mechanism to increase not only rates of return to sport but also preparedness upon return. However, research into the psychosocial management of ACLR is a relatively new field, and systematic investigation is still needed.

Disclosure The authors acknowledge no financial interest or benefit that has arisen from the direct application of this activity.

References

1. Ardern CL, Taylor NF, Feller JA, Webster KE, et al. Br J Sports Med. 2013;47(17):1120–6.
2. Ardern CL. Anterior cruciate ligament reconstruction-not exactly a one-way ticket Back to the Preinjury level: a review of contextual factors affecting return to sport after surgery. Sports Health. 2015;7(3):224–30.
3. Czuppon S, Racette BA, Klein SE, Harris-Hayes M. Variables associated with return to sport following anterior cruciate ligament reconstruction: a systematic review. Br J Sports Med. 2014;48(5):356–64.
4. Walker N, Thatcher J, Lavallee D. Psychological responses to injury in competitive sport: a critical review. J R Soc Promot Heal. 2007;127(4):174–80.
5. Morrey MA, Stuart MJ, Smith AM, Wiese-Bjornstal DM. A longitudinal examination of athletes' emotional and cognitive responses to anterior cruciate ligament injury. Clin J Sport Med. 1999;9(2):63–9.
6. Tracey J. The emotional response to the injury and rehabilitation process. J Appl Sport Psychol. 2003;15(4):279–93.
7. Crossman J. Psychological rehabilitation from sports injuries. Sports Med. 1997;23(5):333–9.
8. Chmielewski TL, Zeppieri G Jr, Lentz TA, Tillman SM, Moser MW, Indelicato PA, et al. Longitudinal

changes in psychosocial factors and their association with knee pain and function after anterior cruciate ligament reconstruction. Phys Ther. 2011;91(9):1355–66.
9. Brewer BW, Cornelius AE, Sklar JH, Van Raalte JL, Tennen H, Armeli S, et al. Pain and negative mood during rehabilitation after anterior cruciate ligament reconstruction: a daily process analysis. Scand J Med Sci Sports. 2007;17(5):520–9.
10. Langford JL, Webster KE, Feller JA. A prospective longitudinal study to assess psychological changes following anterior cruciate ligament reconstruction surgery. Br J Sports Med. 2009;43(5):377–81.
11. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. Br J Sports Med. 2011;45(7):596–606.
12. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med. 2014;48(21):1543–52.
13. Podlog L, Eklund RC. The psychosocial aspects of a return to sport following serious injury: a review of the literature from a self-determination perspective. Psychol Sport Exerc. 2007;8(4):535–66.
14. Wiese-Bjornstal DM, Smith AM, Shaffer SM, Morrey MA. An integrated model of response to sport injury: psychological and sociological dynamics. J Appl Sport Psychol. 1998;10(1):46–69.
15. Ardern CL, Glasgow P, Schneiders A, Witvrouw E, Clarsen B, Cools A, et al. 2016 consensus statement on return to sport from the first world congress in sports physical therapy, Bern. Br J Sports Med. 2016;50(14):853–64.
16. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. Sports Med. 2004;34(4):269–80.
17. Ardern CL, Kvist J, Webster KE. Psychological aspects of anterior cruciate ligament injuries. Oper Tech Sports Med. 2016;24(1):77–83.
18. Burland JP, Toonstra J, Werner JL, Mattacola CG, Howell DM, Howard JS. Decision to return to sport after anterior cruciate ligament reconstruction, part I: a qualitative investigation of psychosocial factors. J Athl Train. 2018;53(5):452–63.
19. Everhart JS, Best TM, Flanigan DC. Psychological predictors of anterior cruciate ligament reconstruction outcomes: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2015;23(3):752–62.
20. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2013;41(7):1549–58.
21. Sonesson S, Kvist J, Ardern C, Osterberg A, Silbernagel KG. Psychological factors are important to return to pre-injury sport activity after anterior cruciate ligament reconstruction: expect and motivate to satisfy. Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1375–84.
22. Feucht MJ, Cotic M, Saier T, Minzlaff P, Plath JE, Imhoff AB, et al. Patient expectations of primary and revision anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2016;24(1):201–7.
23. McVeigh F, Pack SM. An exploration of sports rehabilitators' and athletic rehabilitation therapists' views on fear of reinjury after anterior cruciate ligament reconstruction. J Sport Rehabil. 2015;24(2):140–50.
24. Scott SM, Perry MA, Sole G. "Not always a straight path": patients' perspectives following anterior cruciate ligament rupture and reconstruction. Disabil Rehabil. 2018;40(19):2311–7.
25. Heijne A, Axelsson K, Werner S, Biguet G. Rehabilitation and recovery after anterior cruciate ligament reconstruction: patients' experiences. Scand J Med Sci Sports. 2008;18(3):325–35.
26. Gobbi A, Francisco R. Factors affecting return to sports after anterior cruciate ligament reconstruction with patellar tendon and hamstring graft: a prospective clinical investigation. Knee Surg Sports Traumatol Arthrosc. 2006;14(10):1021–8.
27. Webster KE, Feller JA, Lambros C. Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. Phys Ther Sport. 2008;9(1):9–15.
28. Smith AM, Scott SG, Ofallon WM, Young ML. Emotional responses of athletes to injury. Mayo Clin Proc. 1990;65(1):38–50.
29. Thomee P, Wahrborg P, Borjesson M, Thomee R, Eriksson BI, Karlsson J. A new instrument for measuring self-efficacy in patients with an anterior cruciate ligament injury. Scand J Med Sci Sports. 2006;16(3):181–7.
30. Waldrop D, Lightsey OR, Ethington CA, Woemmel CA, Coke AL. Self-efficacy, optimism, health competence, and recovery from orthopedic surgery. J Couns Psychol. 2001;48(2):233–8.
31. Woby SR, Roach NK, Urmston M, Watson PJ. Psychometric properties of the TSK-11: a shortened version of the Tampa Scale for Kinesiophobia. Pain. 2005;117(1–2):137–44.
32. Kori SH, Miller RP, Todd DD. Kinesiophobia: a new region of chronic pain behavior. Pain Manag. 1990;3:35–43.
33. Faltstrom A, Hagglund M, Kvist J. Factors associated with playing football after anterior cruciate ligament reconstruction in female football players. Scand J Med Sci Sports. 2016;26(11):1343–52.
34. Brewer BW, Van Raalte JL, Cornelius AE, Petitpas AJ, Sklar JH, Pohlman MH, et al. Psychological factors, rehabilitation adherence, and rehabilitation outcome after anterior cruciate ligament reconstruction. Rehabil Psychol. 2000;45(1):20–37.
35. DiSanti J, Lisee C, Erickson K, Bell D, Shingles M, Kuenze C. Perceptions of rehabilitation and return to sport among high school athletes with ACL

reconstruction: a qualitative research study. J Orthop Sports Phys Ther. 2018;48(12):951–9.
36. Bandura A. Self-efficacy: toward a unifying theory of behavioral change. Psychol Rev. 1977;84(2):191–215.
37. Thomee P, Wahrborg P, Borjesson M, Thomee R, Eriksson BI, Karlsson J. Self-efficacy of knee function as a pre-operative predictor of outcome 1 year after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2008;16(2):118–27.
38. Hamrin Senorski E, Samuelsson K, Thomee C, Beischer S, Karlsson J, Thomee R. Return to knee-strenuous sport after anterior cruciate ligament reconstruction: a report from a rehabilitation outcome registry of patient characteristics. Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1364–74.
39. Chmielewski TL, George SZ. Fear avoidance and self-efficacy at 4 weeks after ACL reconstruction are associated with early impairment resolution and readiness for advanced rehabilitation. Knee Surg Sports Traumatol Arthrosc. 2019;27(2):397–404.
40. Wu HH, Liu M, Dines JS, Kelly JD, Garcia GH. Depression and psychiatric disease associated with outcomes after anterior cruciate ligament reconstruction. World J Orthop. 2016;7(11):709–17.
41. Garcia GH, Wu HH, Park MJ, Tjoumakaris FP, Tucker BS, Kelly JD, et al. Depression symptomatology and anterior cruciate ligament injury: incidence and effect on functional outcome--a prospective cohort study. Am J Sports Med. 2016;44(3):572–9.
42. Tripp DA, Stanish W, Ebel-Lam A, Brewer BW, Birchard J. Fear of reinjury, negative affect, and catastrophizing predicting return to sport in recreational athletes with anterior cruciate ligament injuries at 1 year postsurgery. Rehabil Psychol. 2007;52(1):74–81.
43. Podlog L, Dimmock J, Miller J. A review of return to sport concerns following injury rehabilitation: practitioner strategies for enhancing recovery outcomes. Phys Ther Sport. 2011;12(1):36–42.
44. Johnson U, Ivarsson A, Karlsson J, Hagglund M, Walden M, Borjesson M. Rehabilitation after first-time anterior cruciate ligament injury and reconstruction in female football players: a study of resilience factors. BMC Sports Sci Med Rehabil. 2016;8:20.
45. Johnston LH, Carroll D. The provision of social support to injured athletes: a qualitative analysis. J Sport Rehabil. 1998;7(4):267–84.
46. Flanigan DC, Everhart JS, Pedroza A, Smith T, Kaeding CC. Fear of reinjury (kinesiophobia) and persistent knee symptoms are common factors for lack of return to sport after anterior cruciate ligament reconstruction. Arthroscopy. 2013;29(8):1322–9.
47. McCullough KA, Phelps KD, Spindler KP, Matava MJ, Dunn WR, Parker RD, et al. Return to high school- and college-level football after anterior cruciate ligament reconstruction: a Multicenter Orthopaedic Outcomes Network (MOON) cohort study. Am J Sports Med. 2012;40(11):2523–9.
48. Ardern CL, Osterberg A, Tagesson S, Gauffin H, Webster KE, Kvist J. The impact of psychological readiness to return to sport and recreational activities after anterior cruciate ligament reconstruction. Br J Sports Med. 2014;48(22):1613–9.
49. Tjong VK, Murnaghan ML, Nyhof-Young JM, Ogilvie-Harris DJ. A qualitative investigation of the decision to return to sport after anterior cruciate ligament reconstruction: to play or not to play. Am J Sports Med. 2014;42(2):336–42.
50. Ardern CL, Taylor NF, Feller JA, Webster KE. Fear of re-injury in people who have returned to sport following anterior cruciate ligament reconstruction surgery. J Sci Med Sport. 2012;15(6):488–95.
51. Kvist J, Ek A, Sporrstedt K, Good L. Fear of re-injury: a hindrance for returning to sports after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2005;13(5):393–7.
52. Chmielewski TL, Jones D, Day T, Tillman SM, Lentz TA, George SZ. The association of pain and fear of movement/reinjury with function during anterior cruciate ligament reconstruction rehabilitation. J Orthop Sports Phys Ther. 2008;38(12):746–53.
53. Lentz TA, Zeppieri G Jr, George SZ, Tillman SM, Moser MW, Farmer KW, et al. Comparison of physical impairment, functional, and psychosocial measures based on fear of reinjury/lack of confidence and return-to-sport status after ACL reconstruction. Am J Sports Med. 2015;43(2):345–53.
54. Paterno MV, Flynn K, Thomas S, Schmitt LC. Self-reported fear predicts functional performance and second ACL injury after ACL reconstruction and return to sport: a pilot study. Sports Health. 2018;10(3):228–33.
55. Podlog L, Banham SM, Wadey R, Hannon JC. Psychological readiness to return to competitive sport following injury: a qualitative study. Sport Psychol. 2015;29(1):1–14.
56. Rosso F, Bonasia DE, Cottino U, Cambursano S, Dettoni F, Rossi R. Factors affecting subjective and objective outcomes and return to play in anterior cruciate ligament reconstruction: a retrospective cohort study. Joints. 2018;6(1):23–32.
57. Han F, Banerjee A, Shen L, Krishna L. Increased compliance with supervised rehabilitation improves functional outcome and return to sport after anterior cruciate ligament reconstruction in recreational athletes. Orthop J Sports Med. 2015;3(12):2325967115620770.
58. Brewer BW, Cornelius AE, Van Raalte JL, Tennen H, Armeli S. Predictors of adherence to home rehabilitation exercises following anterior cruciate ligament reconstruction. Rehabil Psychol. 2013;58(1):64–72.
59. Niven A. Rehabilitation adherence in sport injury: sport physiotherapists' perceptions. J Sport Rehabil. 2007;16(2):93–110.
60. Niven A, Nevill A, Sayers F, Cullen M. Predictors of rehabilitation intention and behavior following anterior cruciate ligament surgery: an application of the theory of planned behavior. Scand J Med Sci Sports. 2012;22(3):316–22.
61. Brewer BW, Cornelius AE, Van Raalte JL, Petitpas AJ, Sklar JH, Pohlman MH, et al. Age-related differences in predictors of adherence to rehabilitation

after anterior cruciate ligament reconstruction. J Athl Train. 2003;38(2):158–62.
62. Chan DK, Lonsdale C, Ho PY, Yung PS, Chan KM. Patient motivation and adherence to postsurgery rehabilitation exercise recommendations: the influence of physiotherapists' autonomy-supportive behaviors. Arch Phys Med Rehabil. 2009;90(12):1977–82.
63. Lentz TA, Paterno MV, Riboh JC. So you think you can return to sport? Br J Sports Med. 2018;52(23):1482–3.
64. Dingenen B, Gokeler A. Optimization of the return-to-sport paradigm after anterior cruciate ligament reconstruction: a critical step back to move forward. Sports Med. 2017;47(8):1487–500.
65. de Mille P, Osmak J. Performance: bridging the gap after ACL surgery. Curr Rev Musculoskelet Med. 2017;10(3):297–306.
66. Ardern CL, Kvist J. What is the evidence to support a psychological component to rehabilitation programs after anterior cruciate ligament reconstruction? Curr Orthop Pract. 2016;27(3):263–8.
67. Coronado RA, Bird ML, Van Hoy EE, Huston LJ, Spindler KP, Archer KR. Do psychosocial interventions improve rehabilitation outcomes after anterior cruciate ligament reconstruction? A systematic review. Clin Rehabil. 2018;32(3):287–98.
68. Cupal DD, Brewer BW. Effects of relaxation and guided imagery on knee strength, reinjury anxiety, and pain following anterior cruciate ligament reconstruction. Rehabil Psychol. 2001;46(1):28–43.
69. Maddison R, Prapavessis H, Clatworthy M, Hall C, Foley L, Harper T, et al. Guided imagery to improve functional outcomes post-anterior cruciate ligament repair: randomized-controlled pilot trial. Scand J Med Sci Sports. 2012;22(6):816–21.
70. Maddison R, Prapavessis H, Clatworthy M. Modeling and rehabilitation following anterior cruciate ligament reconstruction. Ann Behav Med. 2006;31(1):89–98.
71. Zaffagnini S, Russo RL, Marcheggiani Muccioli GM, Marcacci M. The Videoinsight(R) method: improving rehabilitation following anterior cruciate ligament reconstruction--a preliminary study. Knee Surg Sports Traumatol Arthrosc. 2013;21(4):851–8.
72. Rock JA, Jones MV. A preliminary investigation into the use of counseling skills in support of rehabilitation from sport injury. J Sport Rehabil. 2002;11(4):284–304.
73. McArdle S. Psychological rehabilitation from anterior cruciate ligament-medial collateral ligament reconstructive surgery: a case study. Sports Health. 2010;2(1):73–7.
74. Mahoney J, Hanrahan S. A brief educational intervention using acceptance and commitment therapy: four injured athletes' experiences. J Clin Sport Psychol. 2011;5:252–73.
75. Ehde DM, Dillworth TM, Turner JA. Cognitive-behavioral therapy for individuals with chronic pain: efficacy, innovations, and directions for research. Am Psychol. 2014;69(2):153–66.
76. Brewer BW. Self-identity and specific vulnerability to depressed mood. J Pers. 1993;61(3):343–64.
77. Sordoni C, Hall C, Forwell L. The use of imagery by athletes during injury rehabilitation. J Sport Rehabil. 2000;9(4):329–38.
78. Meierbachtol A, Yungtum W, Paur E, Bottoms J, Chmielewski TL. Psychological and functional readiness for sport following advanced group training in patients with anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2018;48(11):864–72.

Part VII

Other Knee Operations

Return to Sport After ACL Revision Reconstruction: Is It Advisable?

25

Frank R. Noyes and Sue Barber-Westin

25.1 Introduction

The majority of patients who undergo primary anterior cruciate ligament (ACL) reconstruction are athletes of <25 years of age [1] whose main goal is to resume their desired sport in an unrestricted manner [2–7]. Unfortunately, as discussed in Chap. 6, reinjuries to either the ACL graft or contralateral ACL frequently occur after patients return to athletics. In individuals <20 years of age, injury rates to ACL grafts and contralateral ACLs have been reported to be as high as 38% [8] and 42% [9], respectively. A study of collegiate athletes reported that those who underwent ACL reconstruction before entering college had an ACL graft reinjury rate during sports competition of 17% and a contralateral ACL injury rate of 20%; the combined reinjury rate (to either knee) was 37% [10].

The majority of young patients who undergo ACL revision reconstruction do so in order to resume sports activities. Patient satisfaction has been directly linked with the ability to return to previous activity levels [2]; however, in the case of ACL revision, the majority of studies report inferior outcomes in many variables compared with primary ACL reconstruction [11–18]. For instance, Wright et al. [18] reviewed 21 studies that followed 863 patients for at least 2 years postoperatively and reported inferior outcomes in ACL revision knees compared with primary ACL knees for mean Cincinnati, Lysholm, and International Knee Documentation Committee (IKDC) scores. Return to unrestricted activities or to the previous sports activity level was reported in 54%. The pooled failure rate of revision reconstructions of 13.7% was 3–4 times that of primary ACL reconstructions (2.9% [19] and 5.8% [20]). Andriolo et al. [21] summarized data from 31 ACL revision studies and reported that 43% (of 1167 patients) returned to previous athletic activity levels, which was significantly lower than the 63% rate reported (from a separate review [22]) after primary ACL reconstruction ($P < 0.05$).

Feucht et al. [23] determined patient expectation of outcome measured before ACL revision surgery in 48 athletes. With regard to the overall condition of the knee joint, 17% expected a normal and 83% anticipated a nearly normal outcome. With regard to return to sports (RTS) at a minimum of 1 year postoperative, 44% expected to return at the same level with no restrictions, 40% at the same level with slight restrictions, 15% at a slightly reduced level, and 2% at a significantly reduced level. Unfortunately, revision ACL study cohorts typically involve patients

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_25

with associated major knee problems, the most frequent of which are prior meniscectomy and articular cartilage damage. The MARS group reported in 1205 patients that 91% had either meniscus and/or articular cartilage damage at the time of the revision procedure [24]. In a study of 393 patients, Wright et al. [18] noted a history of meniscectomy in 54% and articular cartilage damage in 56% at the time of revision surgery. Chen et al. [25] reported in a cohort of 1049 patients undergoing ACL revision that 46% required concomitant meniscectomy and 46% had articular cartilage damage. Some patients who require ACL revision may have painful limited knee motion, undiagnosed or untreated lower limb malalignment, or damage to other knee ligaments. Many have undergone multiple prior operations that did not achieve the desired outcome. These challenges would be expected to directly affect the expected outcomes of revision procedures in terms of RTS. The question of whether return to strenuous activity levels in ACL revision knees is advisable in light of the complexities involved requires analysis of existing investigations.

This chapter summarizes findings from 20 modern studies that provided RTS data in ACL revision knees: fourteen investigations reported data from athletes of all ages, one study focused on skeletally mature athletes of 15–18 years of age, one study reported on patients <25 years of age, one study analyzed three different athlete groups (school, collegiate, and recreational), two studies reported results from patients who underwent multiple ACL revision reconstructions, and one study focused on professional athletes from the National Football League (NFL).

25.2 Return to Sport: Rates and Influential Factors from Clinical Studies

Table 25.1 summarizes data regarding RTS after ACL revision reconstructions [11, 12, 14–17, 26–39]. Validated questionnaires were used to determine preoperative and postoperative sports activity levels in 12 studies, and nonvalidated surveys were used in eight investigations. Return to preinjury sport activity level rates varied widely, from 13% to 100%, and were not associated with the time postoperatively data were collected (Fig. 25.1). Fifteen studies reported the percent of patients who returned to any sport after ACL revision reconstruction, which ranged from 43% to 100%.

Two studies reported factors that were associated with sports activity levels postoperatively. The MARS group [28] found three factors that predicted improved Marx scores 2 years postoperatively: a higher baseline Marx score [33] (OR 5.79, $P < 0.001$), male gender (OR 1.79, $P < 0.001$), and younger age (OR 2.17, $P < 0.001$). Conversely, predictors of lower Marx scores were smoking (OR 1.75, $P < 0.05$), previous contralateral ACL surgery (OR 1.49, $P < 0.05$), and use of a biological enhancement at the time of revision (OR 1.82, $P < 0.05$). Patients who received autografts had significantly higher scores on IKDC and Knee Injury and Osteoarthritis Outcome Score (KOOS) outcome instruments compared with those who received allografts. Anand et al. [33] reported two significant predictors of return to preinjury activity levels after ACL revision: age < 25 years ($P < 0.05$) and articular cartilage lesions of <50% of the depth of the surface ($P < 0.05$). In this study, there were no differences in the number of patients that returned to preinjury sport according to the graft source (bone–patellar tendon–bone [BPTB] and hamstring autografts).

Several studies compared RTS data between primary and revision ACL reconstructions. One investigation retrospectively compared outcomes of 56 ACL revisions with 52 ACL primary reconstruction cases (91% of all patients received BPTB autografts) at a mean of 7.5 years postoperatively [12]. The percentage of patients that returned to the same or higher sports activity level was significantly lower in the revision group compared with the primary group (13% and 35%, respectively, $P < 0.01$). Anand et al. [33] followed a group of 109 patients who all participated in jumping, pivoting, or cutting sports before the original ACL injury and in whom all underwent both primary and subsequent revision

Table 25.1 Return to sport after revision ACL-reconstruction

Study	Cohort			ACL revision graft[a]/no. revisions	Sports scale (preinjury sports)	Criteria to RTS	RTS data		Reinjury/failure data	
	No. of men, women	Mean age (range)	Mean follow-up year				RTS percentages	RTS comments	ACL-R	Contralateral
Okoroha et al. [26]	24, 0	26.3 (21–34)	NP	NP; all one revision	NFL	NP	NFL 79%	Only significant association players drafted <4 rounds ($P = 0.05$). Played fewer games and seasons than preinjury ($P = 0.01$), but not significantly different than control group	NP	NP
Ra et al. [27]	12, 5	32.6 (NP)	2.7	Achilles tendon allograft 100%; all first revision	Tegner (levels 5–8)	Usually at 9 months	Preinjury 100%	NP	0%	NP
The MARS group [28]	Total 980 with Marx scores	26 (NP)	2	Variety; majority first revision (number NP in subgroup with Marx scores)	Marx (NP)	NP	Preinjury 78%, lower 18%, none 4%	Predictors improved Marx score: higher baseline Marx score, male gender, younger age. Predictors lower Marx score: smoking, previous contralateral ACL reconstruction, use of biological enhancement at revision surgery	NP in subgroup with Marx scores	NP

(continued)

Table 25.1 (continued)

Study	Cohort			ACL revision graft[a]/no. revisions	Sports scale (preinjury sports)	Criteria to RTS	RTS data		Reinjury/failure data	
	No. of men, women	Mean age (range)	Mean follow-up year				RTS percentages	RTS comments	ACL-R	Contralateral
Shelbourne et al. [29]	Total 259	High school group 16.6, college group 21.9, adult recreational group 27.6	5	BPTB 81%, hamstring 7%, allograft 4%, other 8%; all one revision	Nonvalidated survey (NP)	<15% deficit quadriceps strength	Preinjury: 74% high school and college groups, 62% recreational group	NP	Traumatic ruptures: high school 2.3%, college 5.1%, recreational 3.4%	Traumatic ruptures: high school 1.1%, college 1.7%, recreational 1.7%
Franceschi et al. [30]	19, 11	29.1 (19–42)	6.7	Hamstring 100%; no. revision NP	NP (NP)	6 months	Preinjury 67%, lower level 23%	NP	0%	NP
Webster et al. [17]	Total 119	18.7 (NP, all <25 years)	4.5	BPTB 62%, Hamstring 36%, 2% allografts; all first revision	Nonvalidated survey (Australian football 49%, basketball 18%, soccer 15%)	NP	Preinjury 65%	Primary reasons for stopping or not returning: fear reinjury, problems with knee, work commitments	Traumatic ruptures: 15% (BPTB 17%, hamstring 11%)	Traumatic ruptures: 12%
Battaglia et al. [11]	36, 27	31 (18–60)	6.1	BPTB 46%, hamstring 32%; no. revision NP	IKDC Sports Activity scale (NP)	Rehabilitation not uniform all patients; RTS based on ability to meet functional landmarks	Unrestricted sports 56%, skiing or tennis 11%, no sports 33%	Major reasons no RTS: knee-related problems 17%, fear 16%	Traumatic ruptures: 4% Atraumatic failure: 21% (specific graft failure rates NP)	NP
Reinhardt et al. [31]	Total 21	16.9 (15–18) All skeletally mature	3	Variety; all first revision	Nonvalidated survey (NP)	<15% deficit hop test, no apprehension sport-specific movements, acceptable flexibility for sports	Preinjury 52%, any sport 95%	No patient was unable to RTS due to knee pain	Traumatic ruptures: 9.5%	NP

Lefevre et al. [14]	40, 15	31.6 (NP)	1	BPTB 53%, hamstring 33%; no. revision NP	Nonvalidated survey (pivoting/contact 64%, pivoting/noncontact 24%, nonpivoting 13%)	NP	Preinjury 49%; same or better level of play 13%; any sport 95%	Major reasons change or stop: 68% knee-related problems, 11% professional reasons, 3% personal reasons	Traumatic ruptures: 1%	NP
Noyes and Barber-Westin [15]	36, 19	27 (14–48)	2.7	BPTB 100%	Cincinnati Sports Activity scale (preoperative: 42% participating in sports with symptoms)	9–12 months if completed running program, no symptoms. Running program begun: no effusion or cartilage damage, >70% quadriceps strength opposite leg, <3 mm increase AP displacement on knee arthrometer test	77% sports, 23% no sports	62% participating without problems, 15% playing with symptoms	Atraumatic failure: 24%	NP
Noyes and Barber-Westin [16]	15, 6	33 (18–52)	4.1	QT 100%; 67% first revision, 33% >2 revisions	Cincinnati Sports Activity scale (preoperative: 76% no sports, 19% low impact)	9–12 months if completed running program, no symptoms	72% sports (48% low impact; 24% running, twisting, turning), 28% no sports	62% participating without problems, 9% playing with symptoms	Atraumatic failure: 5%	NP
Salmon et al. [32]	Total 50	27 (15–39)	7.5	Hamstring 100%	IKDC (NP)	12 months if rehabilitation goals met	58% level I–II (strenuous or moderate)	22% knee had moderate or severe effect knee condition	Traumatic ruptures: 8% Atraumatic failure: 2%	NP

(continued)

Table 25.1 (continued)

Study	Cohort			ACL revision graft[a]/no. revisions	Sports scale (preinjury sports)	Criteria to RTS	RTS data		Reinjury/failure data	
	No. of men, women	Mean age (range)	Mean follow-up year				RTS percentages	RTS comments	ACL-R	Contralateral
Anand et al. [33]	80, 29	28 (NP)	4.9	Hamstring 59%, BPTB 32%, allografts 9%; all one revision	Marx (jumping, pivoting, cutting 100%)	NP	Preinjury 46%, lower level 26%, no sports 28%. Similar compared with primary ACL reconstruction (50% preinjury, 28% lower, 22% none)	Predictors return preinjury: <25 years age ($P < 0.05$), <50% thickness articular cartilage lesions ($P < 0.05$)	Traumatic ruptures: 13% (specific graft failure rates NP)	4.5%
Keizer et al. [34]	Total 55	25.9 autograft, 26.7 allograft	2	BPTB 45%, BPTB allograft 55%; all one revision	Tegner (NP)	NP	BPTB autograft: preinjury 24%, any sport 75% BPTB allograft: preinjury 20%, lower level 43%	Major reasons no RTS: fear reinjury, knee-related problems	NP	NP
Mirouse et al. [35]	11, 29	26.8 (17–46)	4.6	Fascia lata autograft 100%; all first revision	Nonvalidated survey (variety)	NP	Preinjury 40%, lower 50%, changed sport 10%	NP	0%	NP
Diamantopoulos et al. [36]	64, 43	38.8 (NP)	6.1	Hamstring 42%, BPTB 38%, QT 20%	Tegner (NP)	>6 months	Preinjury 36%	NP	Atraumatic failure: 10% (specific graft failure rates NP)	NP
Ferretti et al. [37]	22, 8	34 (21–39)	5	Hamstring 100%	Tegner (NP)	NP	Preinjury sport and level 20%, preinjury sport lower level 30%, lower level 50%	Major reasons change in sport: fear reinjury, personal reasons	Atraumatic failure: 10% (specific graft failure rates NP)	NP

Gifstad et al. [12]	25, 31	34 (20–56)	7.5	BPTB 96%, hamstring 4%; all first revision	Tegner (NP)	After 6 months if quadriceps and hamstrings strength "restored," controlled functional training carried out without difficulty	Preinjury 13%	Return preinjury significantly less compared with primary ACL group (35%, $P = 0.006$)	Atraumatic failure: 20%	NP
Griffith et al. [38]	8, 7	27 (18–57)	5	BPTB allograft 80%, hamstring 13%, BPTB 7%; all second revisions	Tegner (NP)	NP	Preinjury 27%	NP	Traumatic ruptures: 13% (specific graft failure rates NP)	NP
Buda et al. [39]	24, 0	30 (19–49)	3.3	Allografts 100%; 83% second revision, 17% third revision	NP (contact [soccer, basketball] 58%, noncontact 42%)	After 9 months	Preinjury 71%, lower 13%, 16% no sports	NP	Atraumatic failure: 8%	NP

BPTB bone–patellar tendon–bone, *NP* not provided, *QT* quadriceps tendon, *RTS* return to sport
[a]Autograft unless otherwise indicated

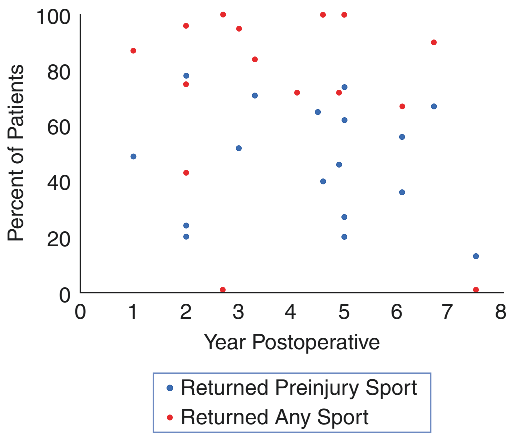


Fig. 25.1 Percentages of patients that returned to their preinjury sport or to any sport after ACL revision reconstruction

reconstructions at a mean of 5 years apart. After the primary ACL reconstruction, 50% returned to the same sports activity level, 28% returned to a lower level, and 22% did not return to sports. A mean of 3 years after the revision procedure, 46% returned to the preinjury sport level, 26% returned to a lower level, and 28% did not return. Webster et al. [17] compared return to preinjury level of sport in 119 patients after their primary and revision ACL reconstruction procedures. These authors reported that although 83% RTS after the primary ACL procedure, only 68% returned after ACL revision. All patients in this cohort were <25 years of age at the time of the revision surgery, and all had been active in athletics before their injury; however, the type of sports patients participated in pre- and postoperatively was not defined.

Lefevre et al. [14] compared outcomes between 55 patients who underwent ACL revision reconstruction with those of 497 patients who underwent ACL primary reconstruction 1 year postoperatively. Approximately 87% of all patients participated in pivoting sports before the original ACL injury. At follow-up, a higher percentage of primary reconstruction patients had returned to their preinjury sport compared with the revision group (64% and 49%, respectively, $P < 0.05$) and had returned to the same or higher level of play (24% and 13%, respectively, $P < 0.05$). There was no difference between groups in the percentage of patients who returned to any sport activity (91% and 87%, respectively).

The most common reasons patients either returned to a lower level of sports or did not return after revision reconstruction included fear of reinjury and knee-related problems [11, 14, 16, 17, 34, 37] Only two studies determined if patients were able to participate in sports without knee-related problems, or if symptoms or functional limitations occurred during or after play. Our study on ACL revision quadriceps tendon autograft reconstruction found 62% (of 21 patients) were participating in mostly low impact activities without problems, and 9% were playing with symptoms [16] (Table 25.2). Our second study on ACL revision BPTB autograft reconstruction reported that 62% (of 51 patients) returned to sports without symptoms, and 15% were participating with symptoms [15]. The Cincinnati Sports Activity Scale [40] allows for the designation of these subgroups, described in detail in Chap. 23.

Only one study focused exclusively on professional athletes. Okoroha et al. [26] identified 24 NFL players who underwent ACL revision during their career. Nineteen players (79%) returned to NFL regular season competition at an

Table 25.2 Sports activity levels before and after ACL revision quadriceps tendon-patellar bone reconstruction [16]

Sport activities	Preoperative	Follow-up
Type of sport		
Jumping, hard pivoting, cutting	5%	0
Running, twisting, turning	0	24%
Swimming, bicycling (low impact)	19%	48%
None	76%	28%
Change in sports activities (from preoperative)		
Increased level, no symptoms		48%
Same level, no symptoms		5%
Decreased level, no symptoms		9%
Playing with symptoms		9%
No sports, knee-related reasons		19%
No sports, non-knee-related reasons		9%

average of 1 year after surgery. The only significant predictor of RTS was a player being drafted in the first four rounds of the NFL draft ($P = 0.05$). Players who returned played in fewer games ($P = 0.01$) and seasons ($P = 0.01$) than before their injury; however, these values were not significantly different compared with controls.

25.3 Reinjury/Failure Rates and Significant Factors

Failure rates of ACL revision grafts (from either traumatic reinjuries or due to atraumatic reasons) reported in 17 studies ranged from 0% to 24% (Fig. 25.2). Many of the graft failures were atraumatic in nature and were detected by physical examination of a positive pivot shift test (grade 2–3) and Lachman (>6 mm increased anteroposterior translation). However, seven studies were conducted by survey only [14, 17, 26, 28, 33–35] and did not include a physical examination. In these instances, the actual graft failure rate may be higher than that reported. Only three studies provided injury rates to the contralateral ACL. The other 17 studies did not specifically state that no contralateral ACL ruptures occurred.

In contrast to studies that reported RTS and failure rates after primary ACL reconstruction (see Chap. 6), few investigations on ACL revision procedures have analyzed factors associated with failure rates related to traumatic reruptures.

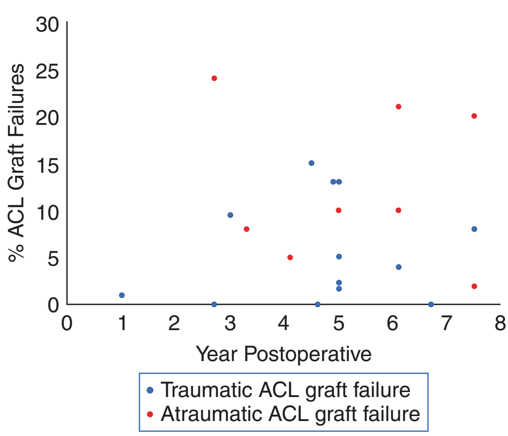


Fig. 25.2 The percentages of ACL graft reruptures or atraumatic failures in ACL revision studies

Shelbourne et al. [29] compared ACL revision failure rates according to age (high school, collegiate, and recreational adult) and found no significant differences (2.3%, 5.1%, and 3.4%, respectively). Webster et al. [17] followed 151 patients who were <25 years old at the time of their revision surgery at a mean of 4.5 years postoperatively. Graft reruptures occurred in 15%; the type of autograft did not influence failure rates (17% BPTB and 11% hamstring). Return to preinjury sport was a significant predictor of a third ACL injury (OR 3.1, $P = 0.02$), as was medial meniscus pathology at the time of revision surgery (OR 3.2, $P = 0.02$).

The effect of the type of graft selected for the revision procedures on graft failure rates from the 20 studies reviewed could not be determined. Seven studies were conducted by survey only [14, 17, 26, 28, 33–35] and did not include a physical examination. In these instances, the actual graft failure rate may be higher than that reported. However, other studies of large cohorts have reported that allografts appear to have higher failure rates compared with B-PT-B and hamstring autografts [41]. In a study of 1205 patients, the MARS group reported that the use of an autograft for ACL revision resulted in patients being 2.78 times less likely to sustain a subsequent graft rupture compared with an allograft ($P < 0.05$) [28]. A second study from this group found that the use of an allograft was a significant predictor for reoperations 2 years postoperatively (OR 1.93, $P < 0.05$) [42]. Future ACL revision studies that involve large cohorts should conduct analyses of potential factors associated with traumatic graft reruptures and atraumatic failure rates, including patient age, gender, sports activity level, concurrent operative procedures, graft used for revision, family history of ACL tears, and muscle strength upon release to activities.

25.4 Criteria for Return to Sports

Criteria for RTS were provided in 11 of the 20 studies (Table 25.3). Two studies [29, 31] provided a single measure of objective criteria, while our two studies [15, 16] provided specific measures for patients to begin running and then to

Table 25.3 Criteria for return to sports

Study	Criteria
Franceschi et al. [30], Diamantopoulos et al. [36]	>6 months
Ra et al. [27], Buda et al. [39]	>9 months
Shelbourne et al. [29]	<15% deficit quadriceps strength
Reinhardt et al. [31]	<15% deficit hop test; no apprehension sports-specific movements, acceptable flexibility for sports
Noyes and Barber-Westin [15], Noyes and Barber-Westin [16]	Running program begun at 6 months if no effusion or cartilage damage, >70% quadriceps strength opposite leg, no more than 3 mm increase anteroposterior displacement on knee arthrometer test. Sports at 9–12 months if completed running program, no symptoms. Patients with articular cartilage damage advised low-impact sports only
Salmon et al. [32]	12 months if rehabilitation goals met
Gifstad et al. [12]	After 6 months if quadriceps and hamstrings strength "restored," controlled functional training carried out without difficulty
Battaglia et al. [11]	Based on ability to meet functional landmarks

resume sports activities. Two studies [30, 36] provided only the amount of time postoperatively patients were typically allowed to resume sports, and three studies [11, 12, 32] provided ambiguous conditions. The lack of criteria provided for RTS in the ACL revision literature limits the ability to determine if release to unrestricted athletic activities before restoration of normal muscle strength and neuromuscular function affected graft rerupture rates.

25.5 Multiple-Revision ACL Reconstruction Studies

Few studies have focused on patients that required more than one ACL revision reconstruction [25, 38, 39, 43–45]. In general, outcomes of multiple-revision ACL reconstruction are inferior to those of primary ACL reconstruction and single-revision procedures. Chen et al. [25] compared results of 1049 single-revision ACL reconstructions with those of 151 multiple-revision reconstructions in the MARS cohort 2 years postoperatively. The multiple-revision group had inferior mean Marx activity level scores compared with the single-revision group (6.74 versus 9.77; $P < 0.05$). No other data related to sports activities was provided. Of note, chondral damage was more prevalent in the multiple-revision group compared with the single-revision group on both the medial femoral condyle (58% and 46%, respectively; $P < 0.05$) and on the patella (39% and 32%, respectively; $P < 0.05$).

Buda et al. [39] followed 24 male athletes (mean age 30) who underwent multiple-revision ACL reconstruction at a mean of 3.3 years postoperatively. Before the original ACL injury, 14 patients participated in soccer or basketball and ten participated in noncontact sports. Twenty-two patients were recreational athletes and two were professionals. All underwent allograft reconstruction and sports were allowed after 9 months (no specific criteria for RTS were provided). Seventeen patients (71%) were able to resume their preinjury sports activities, three (13%) participated in lower level activities, and four (16%) did not return to sports. The mechanism of the reinjury to the primary ACL graft was associated with RTS because 87.5% of patients who sustained a traumatic reinjury returned to their preinjury sports level, while only 37.5% of patients who experienced an atraumatic graft failure resumed preinjury activities ($P = 0.009$).

Griffith et al. [38] followed 15 patients (eight men, seven women; mean age, 27) who underwent multiple-revision ACL reconstruction at a mean of 5 years postoperatively. All patients had undergone two revision procedures, 73% also underwent meniscectomy, and 67% had grade 3 or 4 International Cartilage Repair Society chondral lesions. Only four (27%) returned to their prior activity level; the mean Tegner score at follow-up was 4.5.

25.6 Conclusions and Future Study Considerations

There were limitations to our review of these 20 studies that may affect RTS data and resulting conclusions. Several studies failed to provide data regarding existing abnormalities such as meniscectomy (ten studies) or articular cartilage damage (nine studies). We could not adequately analyze the potential effect of concomitant ligament reconstruction or other major procedures because only five investigations included associated procedures in the study cohort. In fact, study design excluded concomitant ligament procedures in eight investigations (Table 25.4). In our experience with ACL revision knees, the majority

Table 25.4 Study exclusionary criteria, concomitant abnormalities, and major associated operative procedures

Study	Study exclusionary factors	Abnormality		Major associated procedure
		Meniscectomy	Articular cartilage damage	
Webster et al. [17]	Concomitant ligament reconstruction, prior ACL revision	74%	14% (grade 2B-3 CKRS)	None
Battaglia et al [11]	Conditions believe to influence accurate data interpretation	51%	24% x-ray moderate–severe (Fairbanks)	5% meniscal transplant, 1% MCL reconstruction, 1% HTO
Lefevre [14]	Concomitant ligament tears	56%	42%	NP for revision subgroup
Noyes and Barber-Westin [15]	None, consecutive series	NP	56% (grade 2B-3 CKRS)	29% posterolateral ligament reconstruction
Noyes and Barber-Westin [16]	None, consecutive series	35%	48% (grade 2B-3 CKRS)	33% HTO (prior or concurrent), 24% posterolateral ligament reconstruction, 5% OAT, 5% extensor mechanism proximal realignment
Anand et al. [33]	Concomitant ligament reconstruction	59%	29% (grade 3–4 ICRS)	None
Franceschi et al. [30]	Concomitant ligament tears, severe DJD, fracture, WC, cardiovascular disease	33%	NP	None
Gifstad et al. [12]	Concomitant ligament reconstruction or HTO, prior ACL revision	NP	NP	NP
Mirouse et al. [35]	Concomitant ligament reconstruction	NP	NP	NP
Keizer et al. [34]	Multiple ACL revisions, revision graft other than BPTB autograft or allograft	NP for subgroup with 2-year results	NP for subgroup with 2-year results	NP for subgroup with 2-year results
Reinhardt et al. [31]	None	NP	NP	NP
Shelbourne et al. [29]	Patient not involved in pivoting, twisting, jumping sports or did not desire to return to preinjury activity level	NP	NP	NP

(continued)

Table 25.4 (continued)

Study	Study exclusionary factors	Abnormality		Major associated procedure
		Meniscectomy	Articular cartilage damage	
The MARS group [28]	Concomitant ligament reconstruction	NP for subgroup with Marx scores	NP for subgroup with Marx scores	NP for subgroup with Marx scores
Ra et al. [27]	Cases where femoral tunnel did not overlap new desired tunnel position	NP	NP	NP
Okoroha et al. [26]	None	NP	NP	NP
Buda et al. [39]	None	75%	25% grade 3, 17% grade 2	None
Griffith et al. [38]	None	73%	67% (grade 3–4 ICRS)	7% MCL reconstruction
Diamantopoulos et al. [36]	None, consecutive series	37%	27% (grade 3–4 Outerbridge)	None
Ferretti et al. [37]	None, consecutive series	NP	10% (grade 3–4 ICRS)	100% extra-articular iliotibial band
Salmon et al. [32]	None, consecutive series	40%	15% (moderate–severe)	None

CKRS Cincinnati knee rating system, *HTO* high tibial osteotomy, *ICRS* International Cartilage Repair Society, *MCL* medial collateral ligament, *NP* not provided, *OAT* osteochondral autograft transfer

(>90%) have compounding problems of meniscectomy, articular cartilage damage, varus malalignment, or concomitant ligament deficiency that affect study outcomes, especially regarding RTS. One study [30] reviewed in this chapter reported that 20 of 30 patients (67%) returned to preoperative sports levels. However, at the 5-year follow-up evaluation, 63% had degenerative joint changes that were significantly associated with meniscectomy (OR 5.8, $P < 0.05$). Whether these patients were participating with knee-related symptoms was not determined. We advise return to low-impact activities after ACL revision in patients who have undergone meniscectomy or in whom arthritic damage or symptoms are present. We have found that after ACL revision reconstruction, approximately 60% of patients are able to participate in activities such as swimming, bicycling, low-impact aerobics, and fitness training without problems and counsel future candidates accordingly.

The effect of patient age at the time of revision surgery on subsequent RTS and reinjury rates remains inconclusive from the data reviewed. Only three studies [17, 29, 31] described younger cohorts; return to preinjury sports activity rates ranged from 52% to 74% and graft failure rates ranged from 2.3% to 15%. As discussed in Chap. 6, injury rates to primary ACL grafts of >15% have been reported in multiple studies in athletes less than 20 years of age [8, 46–50].

The mean follow-up in the 20 studies was short to mid-term (range, 1–7.5 years). The question of the whether patients are able to participate in athletic activities without developing symptoms and/or arthritic joint changes for many years after ACL revision reconstruction remains unanswered. Third, only our studies provided data on whether symptoms and/or functional limitations were incurred with sports activities. The potential deleterious effects of pain, swelling, or instability incurred with athletics require further attention. Future investigations should report the percentage of patients who return to specific activities without symptoms, as well as those who experience problems or limitations.

Fourth, few studies described criteria required for release to unrestricted sports activities. It is unclear whether traumatic ACL revision graft reruptures occur because of the failure to restore normal muscle strength and neuromuscular indices or because of other reasons. With the ever-increasing number of ACL revision procedures performed each year, future studies should carefully describe these criteria.

Finally, the use of survey-only methods to obtain RTS data contains inherent problems. The implementation of nonvalidated questionnaires is questionable, especially in light of the fact that there exist sports activity assessment methods that have proven reliability, validity, and responsiveness qualities [51] (see Chap. 23). The reasons for change in sports levels or failure to resume athletics after surgery should be determined in a rigorous manner.

References

1. Sanders TL, Maradit Kremers H, Bryan AJ, Larson DR, Dahm DL, Levy BA, Stuart MJ, Krych AJ. Incidence of anterior cruciate ligament tears and reconstruction: a 21-year population-based study. Am J Sports Med. 2016;44(6):1502–7. https://doi.org/10.1177/0363546516629944.
2. Ardern CL, Osterberg A, Sonesson S, Gauffin H, Webster KE, Kvist J. Satisfaction with knee function after primary anterior cruciate ligament reconstruction is associated with self-efficacy, quality of life, and returning to the preinjury physical activity. Arthroscopy. 2016;32(8):1631–1638 e1633. https://doi.org/10.1016/j.arthro.2016.01.035.
3. Ardern CL, Osterberg A, Tagesson S, Gauffin H, Webster KE, Kvist J. The impact of psychological readiness to return to sport and recreational activities after anterior cruciate ligament reconstruction. Br J Sports Med. 2014;48(22):1613–9. https://doi.org/10.1136/bjsports-2014-093842.
4. Filbay SR, Ackerman IN, Russell TG, Crossley KM. Return to sport matters-longer-term quality of life after ACL reconstruction in people with knee difficulties. Scand J Med Sci Sports. 2017;27(5):514–24. https://doi.org/10.1111/sms.12698.
5. Novaretti JV, Franciozi CE, Forgas A, Sasaki PH, Ingham SJM, Abdalla RJ. Quadriceps strength deficit at 6 months after ACL reconstruction does not predict return to preinjury sports level. Sports Health. 2018;10(3):266–71. https://doi.org/10.1177/1941738118759911.
6. Nwachukwu BU, Voleti PB, Berkanish P, Chang B, Cohn MR, Williams RJ 3rd, Allen AA. Return to play and patient satisfaction after ACL reconstruction: study with minimum 2-year follow-up. J Bone Joint Surg Am. 2017;99(9):720–5. https://doi.org/10.2106/JBJS.16.00958.
7. Sonesson S, Kvist J, Ardern C, Osterberg A, Silbernagel KG. Psychological factors are important to return to pre-injury sport activity after anterior cruciate ligament reconstruction: expect and motivate to satisfy. Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1375–84. https://doi.org/10.1007/s00167-016-4294-8.
8. Salmon LJ, Heath E, Akrawi H, Roe JP, Linklater J, Pinczewski LA. 20-year outcomes of anterior cruciate ligament reconstruction with hamstring tendon autograft: the catastrophic effect of age and posterior tibial slope. Am J Sports Med. 2018;46(3):531–43. https://doi.org/10.1177/0363546517741497.
9. Placella G, Bartoli M, Peruzzi M, Speziali A, Pace V, Cerulli G. Return to sport activity after anterior cruciate ligament reconstruction in skeletally immature athletes with manual drilling original all inside reconstruction at 8 years follow-up. Acta Orthop Traumatol Turc. 2016;50(6):635–8. https://doi.org/10.1016/j.aott.2016.03.006.
10. Kamath GV, Murphy T, Creighton RA, Viradia N, Taft TN, Spang JT. Anterior cruciate ligament injury, return to play, and reinjury in the elite collegiate athlete: analysis of an NCAA division I cohort. Am J Sports Med. 2014;42(7):1638–43. https://doi.org/10.1177/0363546514524164.
11. Battaglia MJ 2nd, Cordasco FA, Hannafin JA, Rodeo SA, O'Brien SJ, Altchek DW, Cavanaugh J, Wickiewicz TL, Warren RF. Results of revision anterior cruciate ligament surgery. Am J Sports Med. 2007;35(12):2057–66. https://doi.org/10.1177/0363546507307391.
12. Gifstad T, Drogset JO, Viset A, Grontvedt T, Hortemo GS. Inferior results after revision ACL reconstructions: a comparison with primary ACL reconstructions. Knee Surg Sports Traumatol Arthrosc. 2013;21(9):2011–8. https://doi.org/10.1007/s00167-012-2336-4.
13. Kievit AJ, Jonkers FJ, Barentsz JH, Blankevoort L. A cross-sectional study comparing the rates of osteoarthritis, laxity, and quality of life in primary and revision anterior cruciate ligament reconstructions. Arthroscopy. 2013;29(5):898–905. https://doi.org/10.1016/j.arthro.2013.01.020.
14. Lefevre N, Klouche S, Mirouse G, Herman S, Gerometta A, Bohu Y. Return to sport after primary and revision anterior cruciate ligament reconstruction: a prospective comparative study of 552 patients from the FAST cohort. Am J Sports Med. 2017;45(1):34–41. https://doi.org/10.1177/0363546516660075.
15. Noyes FR, Barber-Westin SD. Revision anterior cruciate surgery with use of bone-patellar tendon-bone autogenous grafts. J Bone Joint Surg Am. 2001;83-A(8):1131–43.
16. Noyes FR, Barber-Westin SD. Anterior cruciate ligament revision reconstruction: results using a quadriceps tendon-patellar bone autograft. Am

J Sports Med. 2006;34(4):553–64. https://doi.org/10.1177/0363546505281812.
17. Webster KE, Feller JA, Kimp AJ, Whitehead TS. Revision anterior cruciate ligament reconstruction outcomes in younger patients: medial meniscal pathology and high rates of return to sport are associated with third ACL injuries. Am J Sports Med. 2018;46(5):1137–42. https://doi.org/10.1177/0363546517751141.
18. Wright RW, Gill CS, Chen L, Brophy RH, Matava MJ, Smith MV, Mall NA. Outcome of revision anterior cruciate ligament reconstruction: a systematic review. J Bone Joint Surg Am. 2012;94(6):531–6. https://doi.org/10.2106/JBJS.K.00733.
19. Wright RW, Dunn WR, Amendola A, Andrish JT, Bergfeld J, Kaeding CC, Marx RG, McCarty EC, Parker RD, Wolcott M, Wolf BR, Spindler KP. Risk of tearing the intact anterior cruciate ligament in the contralateral knee and rupturing the anterior cruciate ligament graft during the first 2 years after anterior cruciate ligament reconstruction: a prospective MOON cohort study. Am J Sports Med. 2007;35(7):1131–4.
20. Wright RW, Magnussen RA, Spindler KP. Ipsilateral graft and contralateral ACL rupture at five years or more following ACL reconstruction. A systematic review. J Bone Joint Surg Am. 2011;92:59–65. https://doi.org/10.2106/JBJSJ.00898.
21. Andriolo L, Filardo G, Kon E, Ricci M, Della Villa F, Della Villa S, Zaffagnini S, Marcacci M. Revision anterior cruciate ligament reconstruction: clinical outcome and evidence for return to sport. Knee Surg Sports Traumatol Arthrosc. 2015;23(10):2825–45. https://doi.org/10.1007/s00167-015-3702-9.
22. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. Br J Sports Med. 2011;45(7):596–606. https://doi.org/10.1136/bjsm.2010.076364.
23. Feucht MJ, Cotic M, Saier T, Minzlaff P, Plath JE, Imhoff AB, Hinterwimmer S. Patient expectations of primary and revision anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2016;24(1):201–7. https://doi.org/10.1007/s00167-014-3364-z.
24. MARS Group. Meniscal and articular cartilage predictors of clinical outcome after revision anterior cruciate ligament reconstruction. Am J Sports Med. 2016;44(7):1671–9. https://doi.org/10.1177/0363546516644218.
25. Chen JL, Allen CR, Stephens TE, Haas AK, Huston LJ, Wright RW, Feeley BT. Differences in mechanisms of failure, intraoperative findings, and surgical characteristics between single- and multiple-revision ACL reconstructions: a MARS cohort study. Am J Sports Med. 2013;41(7):1571–8. https://doi.org/10.1177/0363546513487980.
26. Okoroha KR, Kadri O, Keller RA, Marshall N, Cizmic Z, Moutzouros V. Return to play after revision anterior cruciate ligament reconstruction in national football league players. Orthop J Sports Med. 2017;5(4):2325967117698788. https://doi.org/10.1177/2325967117698788.
27. Ra HJ, Ha JK, Kim JG. One-stage revision anterior cruciate ligament reconstruction with impacted bone graft after failed primary reconstruction. Orthopedics. 2013;36(11):860–3. https://doi.org/10.3928/01477447-20131021-07.
28. MARS group. Effect of graft choice on the outcome of revision anterior cruciate ligament reconstruction in the multicenter ACL revision study (MARS) cohort. Am J Sports Med. 2014;42(10):2301–10. https://doi.org/10.1177/0363546514549005.
29. Shelbourne KD, Benner RW, Gray T. Return to sports and subsequent injury rates after revision anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med. 2014;42(6):1395–400. https://doi.org/10.1177/0363546514524921.
30. Franceschi F, Papalia R, Del Buono A, Zampogna B, Diaz Balzani L, Maffulli N, Denaro V. Two-stage procedure in anterior cruciate ligament revision surgery: a five-year follow-up prospective study. Int Orthop. 2013;37(7):1369–74. https://doi.org/10.1007/s00264-013-1886-5.
31. Reinhardt KR, Hammoud S, Bowers AL, Umunna BP, Cordasco FA. Revision ACL reconstruction in skeletally mature athletes younger than 18 years. Clin Orthop Relat Res. 2012;470(3):835–42. https://doi.org/10.1007/s11999-011-1956-1.
32. Salmon LJ, Pinczewski LA, Russell VJ, Refshauge K. Revision anterior cruciate ligament reconstruction with hamstring tendon autograft: 5- to 9-year follow-up. Am J Sports Med. 2006;34(10):1604–14.
33. Anand BS, Feller JA, Richmond AK, Webster KE. Return-to-sport outcomes after revision anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2016;44(3):580–4. https://doi.org/10.1177/0363546515618381.
34. Keizer MNJ, Hoogeslag RAG, van Raay J, Otten E, Brouwer RW. Superior return to sports rate after patellar tendon autograft over patellar tendon allograft in revision anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2018;26(2):574–81. https://doi.org/10.1007/s00167-017-4612-9.
35. Mirouse G, Rousseau R, Casabianca L, Ettori MA, Granger B, Pascal-Moussellard H, Khiami F. Return to sports and functional results after revision anterior cruciate ligament reconstruction by fascia lata autograft. Orthop Traumatol Surg Res. 2016;102(7):863–6. https://doi.org/10.1016/j.otsr.2016.06.017.
36. Diamantopoulos AP, Lorbach O, Paessler HH. Anterior cruciate ligament revision reconstruction: results in 107 patients. Am J Sports Med. 2008;36(5):851–60.
37. Ferretti A, Conteduca F, Monaco E, De Carli A, D'Arrigo C. Revision anterior cruciate ligament reconstruction with doubled semitendinosus and gracilis tendons and lateral extra-articular reconstruction. J Bone Joint Surg Am. 2006;88(11):2373–9.

38. Griffith TB, Allen BJ, Levy BA, Stuart MJ, Dahm DL. Outcomes of repeat revision anterior cruciate ligament reconstruction. Am J Sports Med. 2013;41(6):1296–301. https://doi.org/10.1177/0363546513482568.
39. Buda R, Ruffilli A, Di Caprio F, Ferruzzi A, Faldini C, Cavallo M, Vannini F, Giannini S. Allograft salvage procedure in multiple-revision anterior cruciate ligament reconstruction. Am J Sports Med. 2013;41(2):402–10. https://doi.org/10.1177/0363546512471025.
40. Noyes FR, Barber SD, Mooar LA. A rationale for assessing sports activity levels and limitations in knee disorders. Clin Orthop Relat Res. 1989;(246):238–49.
41. Noyes FR, Barber-Westin SD. 8 - Anterior cruciate ligament revision reconstruction: graft options and clinical outcomes. In: Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Amsterdam: Elsevier; 2017. p. 221–57. https://doi.org/10.1016/B978-0-323-32903-3.00008-1.
42. Ding DY, Zhang AL, Allen CR, Anderson AF, Cooper DE, DeBerardino TM, Dunn WR, Haas AK, Huston LJ, Lantz BBA, Mann B, Spindler KP, Stuart MJ, Wright RW, Albright JP, Amendola AN, Andrish JT, Annunziata CC, Arciero RA, Bach BR Jr, Baker CL 3rd, Bartolozzi AR, Baumgarten KM, Bechler JR, Berg JH, Bernas GA, Brockmeier SF, Brophy RH, Bush-Joseph CA, JBt B, Campbell JD, Carey JL, Carpenter JE, Cole BJ, Cooper JM, Cox CL, Creighton RA, Dahm DL, David TS, Flanigan DC, Frederick RW, Ganley TJ, Garofoli EA, Gatt CJ Jr, Gecha SR, Giffin JR, Hame SL, Hannafin JA, Harner CD, Harris NL Jr, Hechtman KS, Hershman EB, Hoellrich RG, Hosea TM, Johnson DC, Johnson TS, Jones MH, Kaeding CC, Kamath GV, Klootwyk TE, Levy BA, Ma CB, Maiers GP 2nd, Marx RG, Matava MJ, Mathien GM, McAllister DR, McCarty EC, McCormack RG, Miller BS, Nissen CW, O'Neill DF, Owens BD, Parker RD, Purnell ML, Ramappa AJ, Rauh MA, Rettig AC, Sekiya JK, Shea KG, Sherman OH, Slauterbeck JR, Smith MV, Spang JT, Svoboda SJ, Taft TN, Tenuta JJ, Tingstad EM, Vidal AF, Viskontas DG, White RA, Williams JS Jr, Wolcott ML, Wolf BR, York JJ. Subsequent surgery after revision anterior cruciate ligament reconstruction: rates and risk factors from a multicenter cohort. Am J Sports Med. 2017;45(9):2068–76. https://doi.org/10.1177/0363546517707207.
43. Dejour D, Saffarini M, Demey G, Baverel L. Tibial slope correction combined with second revision ACL produces good knee stability and prevents graft rupture. Knee Surg Sports Traumatol Arthrosc. 2015;23(10):2846–52. https://doi.org/10.1007/s00167-015-3758-6.
44. Sonnery-Cottet B, Mogos S, Thaunat M, Archbold P, Fayard JM, Freychet B, Clechet J, Chambat P. Proximal tibial anterior closing wedge osteotomy in repeat revision of anterior cruciate ligament reconstruction. Am J Sports Med. 2014;42(8):1873–80. https://doi.org/10.1177/0363546514534938.
45. Wegrzyn J, Chouteau J, Philippot R, Fessy MH, Moyen B. Repeat revision of anterior cruciate ligament reconstruction: a retrospective review of management and outcome of 10 patients with an average 3-year follow-up. Am J Sports Med. 2009;37(4):776–85. https://doi.org/10.1177/0363546508330141.
46. Takazawa Y, Ikeda H, Saita Y, Kawasaki T, Ishijima M, Nagayama M, Kaneko H, Kaneko K. Return to play of rugby players after anterior cruciate ligament reconstruction using hamstring autograft: return to sports and graft failure according to age. Arthroscopy. 2017;33(1):181–9. https://doi.org/10.1016/j.arthro.2016.06.009.
47. Dekker TJ, Godin JA, Dale KM, Garrett WE, Taylor DC, Riboh JC. Return to sport after Pediatric anterior cruciate ligament reconstruction and its effect on subsequent anterior cruciate ligament injury. J Bone Joint Surg Am. 2017;99(11):897–904. https://doi.org/10.2106/JBJS.16.00758.
48. Morgan MD, Salmon LJ, Waller A, Roe JP, Pinczewski LA. Fifteen-year survival of endoscopic anterior cruciate ligament reconstruction in patients aged 18 years and younger. Am J Sports Med. 2016;44(2):384–92. https://doi.org/10.1177/0363546515623032.
49. Edwards PH, Grana WA. Anterior cruciate ligament reconstruction in the immature athlete: long-term results of intra-articular reconstruction. Am J Knee Surg. 2001;14(4):232–7.
50. Ellis HB, Matheny LM, Briggs KK, Pennock AT, Steadman JR. Outcomes and revision rate after bone-patellar tendon-bone allograft versus autograft anterior cruciate ligament reconstruction in patients aged 18 years or younger with closed physes. Arthroscopy. 2012;28(12):1819–25. https://doi.org/10.1016/j.arthro.2012.06.016.
51. Barber-Westin SD, Noyes FR, McCloskey JW. Rigorous statistical reliability, validity, and responsiveness testing of the Cincinnati knee rating system in 350 subjects with uninjured, injured, or anterior cruciate ligament-reconstructed knees. Am J Sports Med. 1999;27(4):402–16.

26 Return-to-Sport Considerations in the Pre-Adolescent Athlete

Jessica L. Traver and Mininder S. Kocher

26.1 Introduction

There has been a significant rise in the number of pediatric anterior cruciate ligament (ACL) tears, as well as pediatric ACL reconstructions performed in the past decade compared with adult counterparts [1]. Between 1994 and 2006, the number of ACL reconstructions performed in patients <15 years of age increased by 924% [2]. One study found that between 2004 and 2017, the number of ACL reconstructions performed for children and adolescents increased nearly three times relative to other orthopedic surgeries [3]. It has been theorized that there have been several factors contributing to this rise in ACL injuries including sports-specialization, year-round training, higher competitive level, and less free play [4].

A recent meta-analysis compared nonoperative to operative intervention in the pediatric population. The authors reported that 13.6% of patients treated operatively demonstrated persistent instability and/or laxity compared with 75% of patients treated nonoperatively. They also found that patients treated nonoperatively were 12 times more likely to have a medial meniscus tear [5]. A recently published study described an electronic survey administered to surgeons attending the Pediatric Research in Sports Medicine (PRiSM) meeting. Of the 85% of respondents, not one elected to pursue nonoperative management in a patient with an ACL injury, regardless of skeletal age [6]. This is vastly different from a study published by Kocher et al. that described a survey performed of the Herodicus Society in 2002 [7]. At that time, only 16% of survey takers selected initial operative management for an 8-year-old child, and 34% selected initial operative management for a 13-year-old child with a complete, acute ACL disruption. An additional 26% and 14%, respectively, selected delayed reconstruction until skeletal maturity.

J. L. Traver · M. S. Kocher (✉)
Division of Sports Medicine, Department of Orthopedics, Boston Children's Hospital, Boston, MA, USA

Harvard Medical School, Boston, MA, USA

The Micheli Center for Sports Injury Prevention, Waltham, MA, USA
e-mail: jessica.traver@childrens.harvard.edu; mininder.kocher@childrens.harvard.edu

26.2 Preoperative Considerations

26.2.1 Skeletal vs. Bone Age

Assessing a patient's bone age compared with their chronological age is a vital component of preoperative planning in the pre-adolescent patient. Skeletal age can be determined by obtaining an anteroposterior [8] hand radiograph and calculating bone age by either using a Greulich and Pyle atlas [9], Sanders bone age [10], or more recently, the HSS short hand bone age method [11].

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_26

26.2.2 Standing Alignment

One potential complication of ACL reconstruction in the pre-adolescent athlete is leg length discrepancy or angular deformity [7]. Part of the preoperative planning work-up should include a hip-to-ankle standing alignment radiograph to assess overall alignment. This is important to be able to identify postoperative growth disturbances (angular deformity, overgrowth, shortening) and treat them appropriately.

26.2.3 Graft Selection

In the skeletally immature patient, it is important to avoid crossing the physis. Bone-patellar-tendon bone (B-PT-B) autografts have limited utility in this patient population because bone blocks crossing the physis may lead to a growth disturbance. Thus, soft tissue grafts (iliotibial band [ITB], hamstring, quadriceps tendon) are usually preferred.

While there are many benefits to using various allografts in ACL reconstruction in the adult population, including decreased operative time and avoidance of graft harvest site morbidity, the same principle is not applicable for the child and pre-adolescent patient. Engelman et al. described a failure rate of up to 29% of pre-adolescent and adolescent patients who received an allograft ACL reconstruction [12]. The authors also found an increase hazard of graft failure to be 4.4 times greater in the allograft group compared to the autograft group. Similarly, a study from the Multicenter Orthopaedic Outcomes Network [10] group found that patients aged 10–19 were four times more likely to retear an allograft compared with an autograft [13].

26.2.4 Partial ACL Tears

In a study evaluating 45 patients, 31% with an arthroscopically documented partial ACL tear treated conservatively required subsequent reconstruction. Risk factors were ACL tears >50%, predominantly posterolateral tears, a grade B pivot-shift test, and older patients. The authors concluded that non-reconstructive management was recommended for partial ACL tears in children and adolescents of 14 years of skeletal age or younger with normal or near normal Lachman and pivot-shift tests [14].

26.3 Surgical Techniques for Skeletally Immature Patients

Regardless of technique chosen, it is important to carefully review all pertinent imaging and skeletal age as part of the preoperative planning of this patient group. A decision-making algorithm considers the age and growth-remaining to assist in appropriate surgical technique selection (Fig. 26.1). One study found that for males of 10, 11 and 12 years of age and females of 11 and 12 years of age, surgeons dual trained in pediatric and sports medicine tended to favor the Micheli/Kocher procedure, while patients with a single sports medicine fellowship favored all-epiphyseal techniques [6]. A variety of other techniques offer surgeons additional flexibility including a hybrid combination of all-epiphyseal femoral tunnel with transphyseal tibial tunnel and a transepiphyseal tibia graft tunnel and over-the-top femoral tunnel placement. A sample of various surgical techniques is depicted in Fig. 26.2.

26.3.1 Micheli/Kocher Technique

The Micheli/Kocher is a non-anatomic, physeal sparing, combined intra-articular and extra-articular reconstruction of the ACL with the use of an autogenous ITB graft [17]. The described technique is indicated for Tanner stage 1 or 2 prepubescent patients. Kocher et al. described a series in which 44 prepubescent patients were followed for a mean of 5.3 years, with a rerupture rate of 4.5% [17]. A recently published study of 237 patients with a mean follow-up of 6.2 years reported that 97% had a grade A pivot shift and a graft rupture rate of 6.6% [18]. Although 48% of patients described thigh asymmetry, only 1.6%

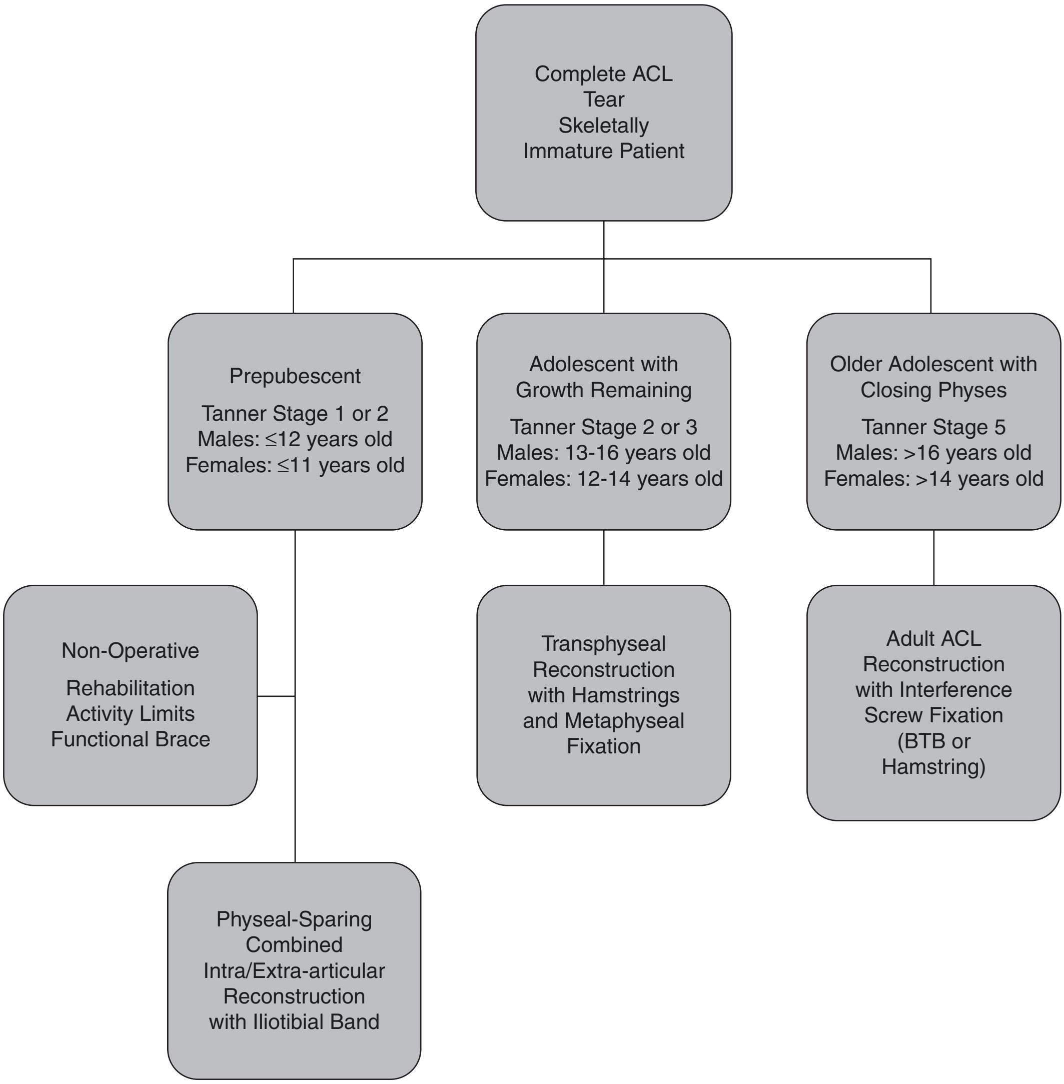


Fig. 26.1 Treatment algorithm for the management of skeletally immature patients (from Lang et al. [15])

had associated pain. There were no cases of leg length discrepancy or angular deformity.

26.3.2 Anderson Technique

The technique pioneered by Anderson is an anatomic, all-epiphyseal tunnel with physeal-sparing technique [19]. Femoral fixation is with a cortical button while tibial fixation is secured to a post just distal to the proximal tibia physis. Lawrence et al. described further evolution of an anatomic, all-epiphyseal tunnel placement with epiphyseal femoral and tibial fixation with either cortical button or interference screw [20].

26.4 Rehabilitation Considerations in the Child/Pre-Adolescent Patient

A combination of unique factors must be considered in the complete, proper rehabilitation of a pre-adolescent patient, including proper proprioceptive training, neuromuscular training, and a goal of obtaining full and symmetric lower

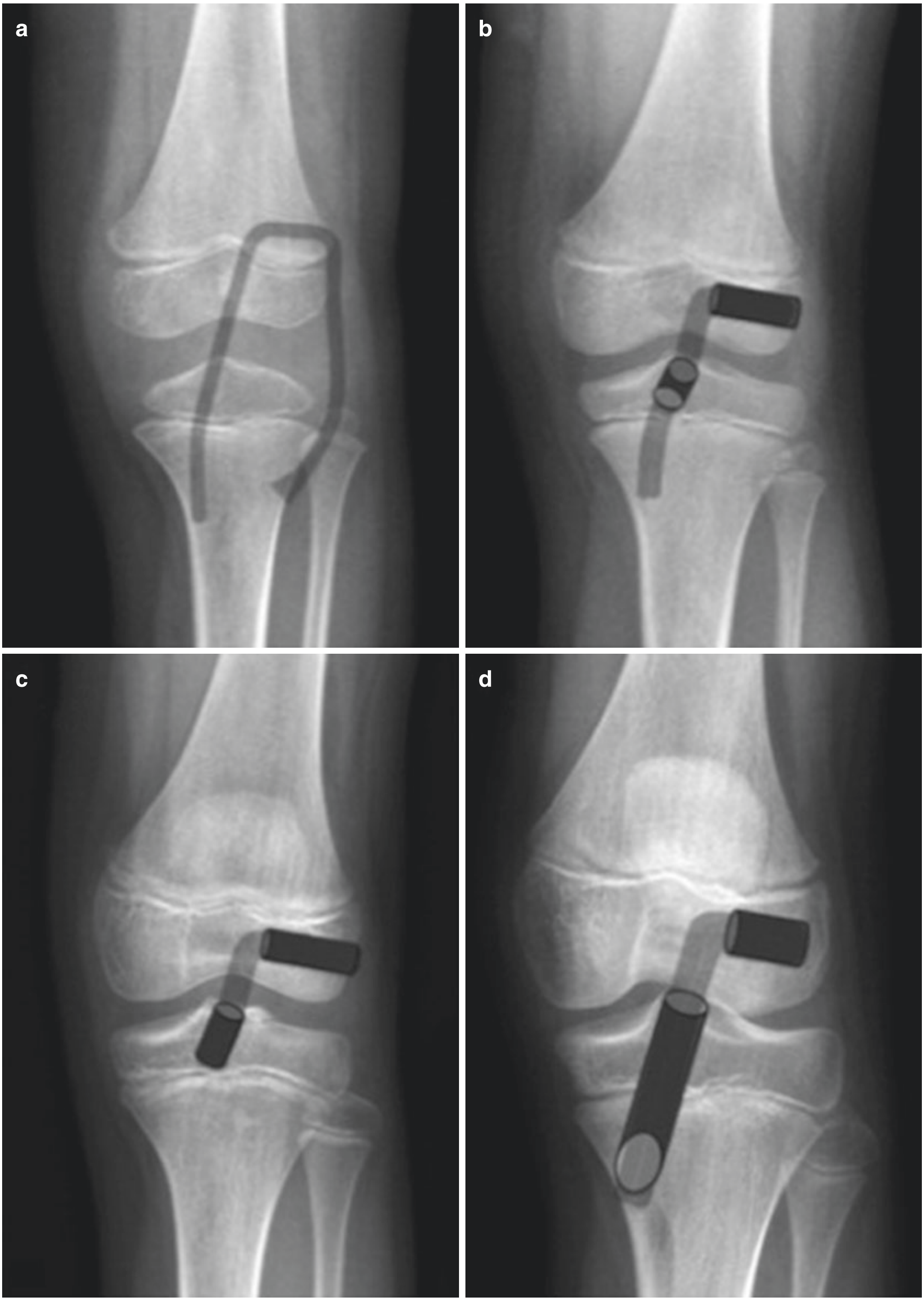


Fig. 26.2 Diagrammatic representation of techniques for skeletally immature patients using (**a**) Micheli–Kocher technique, (**b**) Anderson technique, (**c**) Lawrence–Ganley technique, (**d**) hybrid reconstruction, and (**e**) transphyseal reconstruction (from Milewski et al. [16])

Fig. 26.2 (continued)

extremity strength. There are certain challenges specific to the pre-adolescent age group, including limited attention span, emotional immaturity, and other behavioral challenges not routinely present in the adolescent or adult populations. It cannot be assumed that patients in this age group can perform rehabilitation exercises properly without supervision. These factors need to be addressed beginning in the immediate postoperative time period. For example, while there are some studies demonstrating no benefit of a continuous passive motion device in the adult or adolescent patient population [21], it is often thought to be clinically helpful in achieving early range of motion and to assist in overcoming the fear and anxiety that can be experienced by a child.

There are several differences in the learning strategies and motivational factors based on the chronological and cognitive age of the patient (Fig. 26.3). Kushner et al. [22] suggested that patients in late childhood (ages 7–9) were motivated best by activities that were fun and relatable, responded to visual demonstrations and

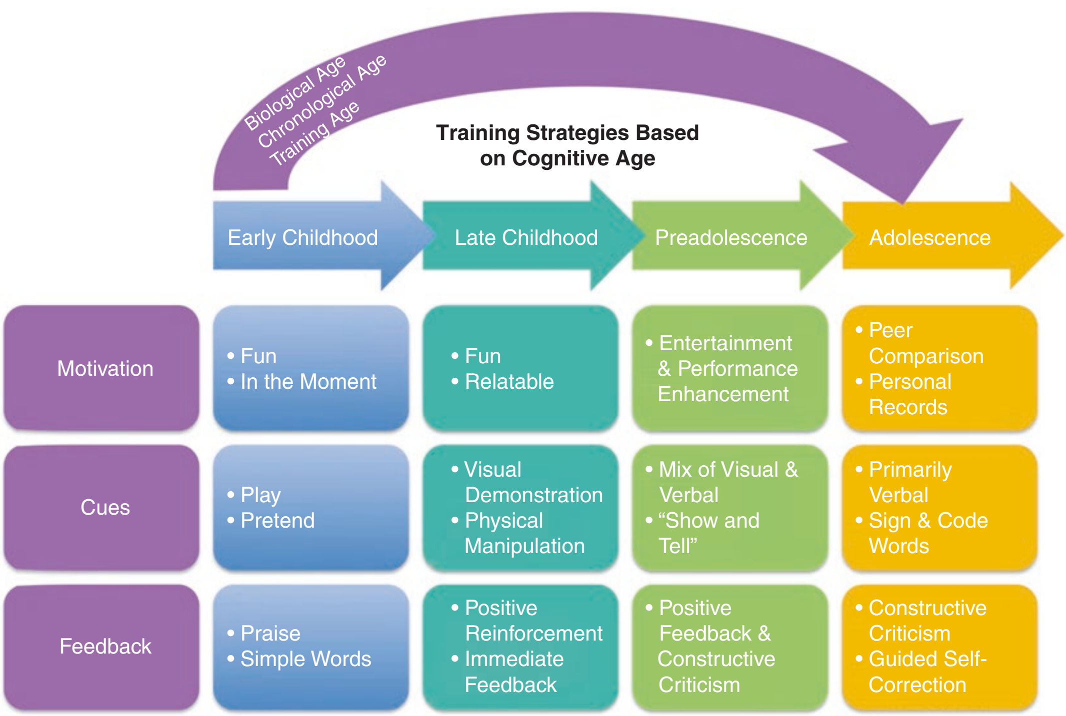


Fig. 26.3 Training strategies relative to motivation, cuing, and feedback associated with each stage of youth development (from Kushner et al. [22])

physical manipulation, and responded to immediate feedback and positive reinforcement. The pre-adolescent (aged 10–11) patients tended to be motivated by entertainment value, responded best to a mix of visual and verbal cues, and responded to positive feedback and constructive criticism. Lastly, the adolescent (aged 12–18) patients were motivated by achieving personal records and comparing milestones with their peers, preferred primarily verbal cues, and responded to constructive criticism and self-correction [22]. These differences should be considered when developing an individualized rehab protocol for each patient.

One should also consider the neuromuscular control maturity of a pre-adolescent patient and how it differs from an adolescent or adult patient. Young pre-adolescent athletes are considered to have underdeveloped coordination, skills, and perception [23]. Hutchinson et al. found that all grade school-aged children (6–13 years old) performed more poorly on both a single-leg balance test and modified drop-jump tests on stable and unstable surfaces compared with collegiate aged athletes [24]. They noted that the differences between the 12- and 13-year-old patients and the collegiate athletes were not significant. Holden et al. found that healthy female athletes with a mean age of 13 demonstrated less knee flexion during landing, as well as less knee varus displacement, compared with male athletes of the same age [25].

Moksnes et al. described several key differences between pediatric and adult patients [26]. These included slower progression to running and jumping to decrease strain across the physis, less use of external loads, home-based functional exercises, and later return to sports (RTS) than adults.

In October 2017, the International Olympic Committee comprised of 21 experts convened to provide a comprehensive list of recommendations specific to the pediatric ACL patient [8]. Although there is limited information on pediatric and prepubescent specific rehabilitation protocols, most advocated a rehabilitation program should be based on functional milestones that are designed to be achieved prior to advancing to the next phase (Table 26.1) [27]. The authors

Table 26.1 Recommended functional tests and return-to-sport criteria for the child and adolescent with ACL injury

For patients who choose ACL reconstruction	
Prehabilitation	• Full active extension and at least 125° of active knee flexion. • Little to no effusion • Ability to hold terminal knee extension during single-leg standing • For adolescents: 90% limb symmetry on muscle strength tests
For patients who choose ACL reconstruction OR nonsurgical treatment	
Phase 1 to phase 2	• Full active knee extension and 120° of active knee flexion • Little to no effusion • Ability to hold terminal knee extension during single-leg standing
Phase 2 to phase 3	• Full knee range of motion • 80% limb symmetry on single-leg hop tests with adequate landing strategies • Ability to jog for 10 min with good form and no subsequent effusion • For adolescents: 80% limb symmetry on muscle strength tests
Phase 3 to phase 4: Sport participation (return-to-sport criteria) and continued injury prevention	• Single-leg hop tests >90% of the contralateral limb (with adequate strategy and movement quality) • Gradual increase in sport-specific training without pain and effusion • Confidence in knee function • Knowledge of high-injury risk knee positioning and ability to maintain low-risk knee positioning in advanced sport-specific actions • Mentally ready to return to sport • For adolescents: 90% limb symmetry on muscle strength tests

From Ardern et al. [8]

Muscle strength testing should be performed with isokinetic dynamometry or handheld dynamometry/1-repetition maximum. The type of test and experience of the tester are highly likely to influence the results. If using handheld dynamometry/1-repetition maximum, consider increasing the limb symmetry criterion cutoff by 10% (i.e., 90% limb symmetry becomes 100% limb symmetry). Clinicians who do not have access to appropriate strength assessment equipment should consider referring the patient elsewhere for strength evaluation provided a list of five important considerations unique to the prepubescent patient with ACL injury [8].

1. Develop a home-based program designed to prevent boredom, but a variety of playful exercises.
2. Recognize that a set of neuromuscular and functional tests, including single-leg hop test and isokinetic strength tests, have larger measurement errors in this patient population.
3. Leg symmetry index is less important to note during single-leg hop testing compared to the overall quality of the movements.
4. Experience in assessing qualitative movements is invaluable, as validated tests have yet to be studied.
5. RTS criteria have yet to be validated in the prepubescent patient population.

Considerations involving graft-specific rehabilitation protocols should be evaluated. Studies have demonstrated that adolescent patients who received B-PT-B had significant deficits in the anterior reach, single hop, triple hops, and crossover hops. The hamstring autograft patients demonstrated deficits in single hop, triple hop, and crossover hops. Patients receiving ITB demonstrated decreased triple hops and 6-m timed hop deficits [28].

26.5 Return-to-Sport Functional Testing

There are several factors to consider when performing RTS functional testing in the pre-adolescent athlete. Yellin et al. performed a systematic review of current literature on rehabilitation following ACL tears. They found that several protocols were based on time frames, with newer protocols involving more milestone-based progression and included incorporating formal prevention programs [29]. A recent retrospective study was done comparing the isokinetic strength testing of both quadriceps and hamstrings, as well as a functional hop test battery (single hop for distance, triple hop for distance, unilateral vertical jump, and unilateral timed lateral hop) at different postoperative time points for patients of 7–15 years old [30]. This study found that at 7 months, patients demonstrated persistent quadriceps strength weakness, with only 56% demonstrating an acceptable limb symmetry index (LSI). Similarly, at 15 months, only 25% of subjects were able to achieve an LSI >90% on all testing parameters. This data suggests that pre-adolescent patients continue to demonstrate persistent functional deficits for over a year following surgery, while 73% of adults were able to achieve >90% performance on similar functional measures by 12 months [31].

Additionally, patients with both symmetrical and asymmetrical strength hop a shorter distance on their contralateral side, meaning that absolute hop distance symmetry alone may not be an adequate test of single-limb function and RTS readiness [32]. A study by Graziano et al. evaluated the clearance of 42 skeletally immature patients aged 10–15 years who underwent ACL reconstruction. They used a combination of quantitative measures, including the LSI, KT-1000 arthrometry, isokinetic strength testing, and sport-specific exercises. These authors also described a Quality of Movement Assessment that was used to clear patients who demonstrated optimal form when changing direction and performing cutting/agility at 100% speed as well as sports-specific drills. The average RTS was 12 months; however, 21% of patients who returned before 12 months sustained a second injury. These investigators concluded that none of the patients were ready to RTS before 9 months secondary to compensatory movement patterns [33].

26.6 Functional Knee Bracing

There is a paucity of literature to recommend either for or against empiric use of functional knee bracing following ACL injuries in the pre-adolescent patient population. A previous study by Sterett et al. in the adult population found that skiers with ACL reconstructed knees were at 2.74 times more likely of sustaining a knee injury and 3.9 times more likely to sustain a knee injury requiring surgery compared with their unbraced cohorts [34]. Dai et al. performed a controlled laboratory study that evaluated adolescent patients who performed a side-cutting task both with and without a functional knee extension-resistant brace. They found that use of the brace did not decrease the limb asymmetries [35]. Birmingham et al. reported that a functional knee brace did not result in an improved outcome compared with a neoprene sleeve following ACL reconstruction in patients aged 14–45; however, the patients did express higher confidence at 12 months and increased help in allowing to RTS compared to those in the sleeve group [36]. Albright and Crepeau suggested that there may be some mental benefit to the adolescent patient population by the functional brace which provides an unquantifiable sense of security and serves as a visual reminder to the players around them [37].

Even with the lack of recommendations supported by evidence-based medicine, a majority of surgeons treating this patient population continue to prescribe functional ACL braces. Patel et al. surveyed 88 surgeons attending the annual PRiSM meeting and asked participants to indicate whether they prescribed functional knee braces after ACL reconstruction in patients 8–15 years old, and if so, for how long. They found that nearly 75% of respondents recommended functional bracing after ACL reconstruction for some period of time, regardless of surgical technique (Table 26.2). In fact, surgeons recommended functional knee brace for at least 24 months following ACL reconstruction in 40% of hybrid technique, 39% of all-epiphyseal techniques, and 52% when using modified McIntosh techniques, respectively, regardless of sport [6]. As such, given the lack of convincing evidence, functional bracing following ACL reconstruction remains controversial.

26.7 Psychological Readiness

There has been a recent surge of interest on potentially modifiable variables that can be addressed when preparing athletes to RTS. Previous studies have primarily focused on performance on functional tests and time since surgery. Several studies have demonstrated that perhaps the psychological impact of injury could influence outcomes. Padaki et al. demonstrated that of all patients between the ages of 10 and 21, 61.5% described avoiding thinking about the injury itself, 37.5% had feelings of numbness regarding their injury, and 37.5% avoided discussing the injury. They found that older patients aged 15–21 years had more psychological trauma, with higher severity of PTSD based on the Horowitz Impact of Event Scale compared with their younger counterparts <14 years old [38]. In a prospective cohort study, Paterno et al. compared patients aged 10–25 and found that patients with increased fear based on a Tampa Scale of Kinesiophobia (TSK-11) score of 19 or higher (indicating greater fear) were 13 times more likely to suffer a second ACL tear within the first 24 months after RTS [39]. They also noted patients with increased fear were seven times more likely to have <95% limb symmetry performance on a hop test and six times more likely to have <90% quadriceps strength symmetry. They suggested that residual fear could lead to altered high-risk movement patterns

Table 26.2 Postoperative functional bracing protocol*

	Modified MacIntosh	All-epiphyseal	Hybrid	Transphyseal
Do not recommend brace	21% (16)	29% (29)	28% (17)	32% (28)
Recommend brace	79% (61)	71% (67)	72% (43)	68% (60)
<12 months	16% (10)	21% (14)	16% (7)	23% (14)
12–17 months	13% (8)	25% (27)	21% (9)	18% (11)
18–23 months	18% (11)	15% (10)	23% (10)	23% (14)
>24 months	52% (32)	39% (26)	40% (17)	35% (21)

From Patel et al. [6]
Data are reported as % (*n*) of respondents. Any discrepancies in percentages totaling to 100% due to rounding

and that this fear should be considered in the RTS algorithm. DiSanti surveyed high school-aged patients who had undergone ACL reconstruction and found that patients reported psychosocial barriers, including sport-based activities associated with the injury, persistent sense of uncertainty regarding full recovery, and social comparison to others with ACL surgery by coaches and parents. These psychosocial concerns were reported with greater frequency than physical barriers or concerns regarding RTS [40]. Coronado et al. performed a systematic review to identify the role of psychosocial interventions in improving patient-reported clinical outcomes. They found that use of guided imagery, relaxation, coping modeling, and visual imagery were used with limited evidence of improving postoperative quality of life, anxiety, or fear of reinjury [41].

Studies have been conducted evaluating the different roles of various people involved in a child's psychosocial support system. Hallquist et al. surveyed coaches, parents, and physiotherapists to evaluate the perceived psychosocial needs of patients of 12–16 years of age who sustained a serious sports injury [42]. They uniformly agreed that there was a lack of communication between all participating parties and lack of a coordinator to ensure the child's every need was met. Coaches felt they did not have the proper education or time to address some of these concerns. Parents demonstrated disappointment for caregivers and personality changes in the child. Physiotherapists believed they interacted with the athlete significantly, but were also not trained to provide psychosocial support.

Along with the personality changes noted by parents, Trentacosta found that of patients younger than 18, almost 40% of those who underwent ligamentous reconstruction failed a test in school after never having done so previously after a reconstruction was performed during the school year [43]. They found that a majority of patients who had surgery during the school year felt their grades were negatively affected by their injury compared to their counterparts who had surgery over a holiday or summer break [43]. Further studies needs to be conducted to evaluate the efficacy of psychosocial intervention and improving functional recovery or influencing RTS following ACL reconstruction in the child or pre-adolescent patient population.

26.8 Factors Affecting Rate of Reinjury

There has been a wide range of reported reinjury rates. One study reported a retear rate as high as 32% in the pediatric patient population [44]. Kay et al. described a combined rate of reinjury of 27%, with 13% of patients sustaining graft failures and 14% of patients sustaining contralateral ACL injuries [45]. A French study compared patients with open physes to those with closed physes and found that the open physes cohort demonstrated return to running at 10.4 months and return to pivoting/contact sports at 13.8 months. They found 9% sustained graft tears and 6% sustained contralateral tears. Thus, these authors suggested that return to pivoting/contact sports should not be allowed until 14 months after surgery in skeletally immature patients [46]. This is slightly longer than the typically used time duration following ACL reconstruction in the USA, where most surgeons allowed skeletally immature patients to RTS by 12 months regardless of surgical technique [6]. Specifically regarding the return to cutting and pivoting sports, the risk of graft failure increased by a factor of 3.9 with the risk of contralateral ACL rupture increasing by a factor of 5 [47].

26.9 Outcomes

The most common question encountered during a preoperative visit of a pre-adolescent patient with an ACL tear is likelihood of returning to play. Kay et al. conducted a meta-analysis combining a total of 20 studies and 1156 patients undergoing ACL reconstructions. The cumulative return to any sport participation was 92%. Return to pre-injury level of sport was 78.6%, and return to competitive level of sport was 81% [45]. Chicorelli et al. found that 96% of skeletally immature athletes of 14 years old or younger were able to return to the same pre-injury skill level. Median time to RTS was 9 months postoperatively, with 85% return by 12 months [48]. Common reasons cited for not returning to previous level of sport included physical limitation, loss of interest, and fear of reinjury [48].

Christino et al. reviewed all revisions performed in patients younger than 18 years and demonstrated a 20% graft reinjury rate, with 15.5% requiring additional surgical procedure after the revision. These patients demonstrated a lower RTS compared to those undergoing primaries. Only 69% of patients RTS, with 55.2% being able to return to the same level of play [49].

26.10 Complications in the Pre-Adolescent Patient

26.10.1 Growth Disturbance

Shea et al. conducted a biomechanical study demonstrating that careful drilling of <5% of the total volume of the physis of either the femur or tibia was associated with minimal risk of growth disturbance [50]. Chotel et al. described two cases of skeletal overgrowth averaging 15 mm in a 7- and 10-year-old patient treated with autologous ITB autograft [51]. Frosch et al. performed a meta-analysis and found an overall risk of leg length difference or mechanical axis deviation to be 2.1% [52]. They also found that transphyseal reconstructions were associated with lower risk of growth disturbances compared to physeal-sparing techniques (1.9% vs. 5.8%). These authors also reported that hamstring grafts were associated with less growth disturbances compared with B–PT–B grafts (2.0% vs. 3.6%). Kocher et al. found that 11% of surgeons in the Herodicus Society had seen a growth disturbance in a skeletally immature patient, 80% of which occurred on the femoral side [7]. These included distal femoral valgus deformity associated with bony bar secondary to a B–PT–B graft, genu valgum without associated bony bar, and leg length discrepancy (both shortening and overgrowth). Because of these risks, current recommendations are to obtain annual long-leg alignment radiographs until the patient reaches skeletal maturity [8].

26.10.2 Arthrofibrosis

The risk of arthrofibrosis is uncommon in pediatric and adolescent patient population. Nwachukwu et al. performed a retrospective case series evaluating patients from 7 to 18 years old. They found an overall incidence rate of arthrofibrosis after ACL reconstruction in children and adolescents to be 8.3%. At the time of final follow-up, almost 90% of the surgically treated patients had full range of motion, 60% were asymptomatic, and 20% complained of some persistent knee pain. Risk factors in this patient population were older adolescents, concurrent meniscal repair, patellar tendon autograft, and female gender. Similarly, Huleatt et al. found an overall rate of manipulation under anesthesia and/or lysis for arthrofibrosis to be 4.5% [53]. They found age <18 years to have an increased relative risk of 2.39.

A recent study evaluated the use of continuous passive motion (CPM) machines following ACL reconstruction in patients younger than 20 years old [54]. They found that 7.4% of patients who did not use a CPM in the immediate postoperative period required MUA within 6 months of surgery while no patients in the CPM cohort required a manipulation. The CPM protocol used in the study was 2 h three times a day for 3 weeks. They concluded that CPM use in the pediatric population was associated with a reduced rate of MUA secondary to arthrofibrosis.

Fabricant et al. found that children and adolescents requiring lysis of adhesions and manipulation under anesthesia resulted in significant knee ROM improvement with 90% revision-free success rate [55]. They also found that preoperative dynamic or static progressive splinting improved preoperative flexion but did not affect final postoperative range of motion.

A known complication of manipulation under anesthesia for arthrofibrosis is iatrogenic femur fracture. This is especially a concern in the pediatric population as a distal femur fracture could cause premature physeal arrest. Vander Have et al. evaluated outcomes in pediatric patients who underwent manipulation for arthrofibrosis following surgical fixation after tibial eminence fractures. The authors noted that three of eight patients managed with manipulation under anesthesia alone sustained distal femur fractures, with two resulting in physeal growth arrest. This was compared with no fractures occurring in a cohort of patients who had arthroscopic lysis of adhesions followed by manipulation under anesthesia. Therefore, the authors recommended that pediatric patients with knee stiffness should only undergo MUA if done in conjunction with arthroscopic lysis of adhesions [56].

26.11 Prevention

There has been increasing interest in developing and implementing ACL injury prevention programs. Mandelbaum et al. reported a series consisting of 1041 female soccer players who received sports-specific training intervention and 1905 patients who participated in a traditional warm-up [57]. They found an 88% decrease in ACL injury after the first year, and a 74% reduction in ACL injuries during the second year. These patients were between the ages of 14 and 18. Recently, the FIFA 11+ for kids program was developed as a child-friendly version of the well-established FIFA 11+ injury prevention program. A European multicenter study recently published that children aged 7–13 demonstrated a significant preventive effect on severe injuries after participating in the FIFA 11+ for kids prevention program for 15–20 min [58]. Similarly, Rossler et al. described a series of nearly 4000 players aged 13 or younger, and found that athletes who participated in the FIFA 11+ for kids once per week demonstrated a decreased overall injury rate of 48% [59]. This is encouraging in the pre-adolescent and adolescent age groups because there have been several studies which demonstrate patient age <19 is a significant risk factor for revision [60, 61].

26.12 Summary

In conclusion, various factors need to be considered when developing a rehabilitation program for a pre-adolescent athlete as they prepare to RTS. Children and pre-adolescent patients have different emotional, mental, and physical characteristics and should not be treated the same as adults. It is important for the patient and families to be appropriately counseled on the possibility of a longer time to RTS and an increased rate of reinjury compared to adults. It is the responsibility of the physician, parents, coaches, and physiotherapists to communicate and work toward a safe RTS while considering the overall well-being of the child as they progress through the various phases of their functional rehabilitation program.

References

1. Werner BC, Yang S, Looney AM, Gwathmey FW Jr. Trends in pediatric and adolescent anterior cruciate ligament injury and reconstruction. J Pediatr Orthop. 2016;36(5):447–52.
2. Dekker TJ, Rush JK, Schmitz MR. What's new in pediatric and adolescent anterior cruciate ligament injuries? J Pediatr Orthop. 2018;38(3):185–92.
3. Tepolt FA, Feldman L, Kocher MS. Trends in pediatric ACL reconstruction from the PHIS database. J Pediatr Orthop. 2018;38(9):e490–4.
4. Frank JS, Gambacorta PL. Anterior cruciate ligament injuries in the skeletally immature athlete: diagnosis and management. J Am Acad Orthop Surg. 2013;21(2):78–87.
5. Ramski DE, Kanj WW, Franklin CC, Baldwin KD, Ganley TJ. Anterior cruciate ligament tears in children and adolescents: a meta-analysis of nonoperative versus operative treatment. Am J Sports Med. 2014;42(11):2769–76.
6. Patel NM, Talathi NS, Talwar D, et al. Factors affecting the preferred surgical technique in pediatric anterior cruciate ligament reconstruction. Orthop J Sports Med. 2018;6(9):2325967118796171.
7. Kocher MS, Saxon HS, Hovis WD, Hawkins RJ. Management and complications of anterior cruciate ligament injuries in skeletally immature patients: survey of the Herodicus Society and The ACL Study Group. J Pediatr Orthop. 2002;22(4):452–7.
8. Ardern CL, Ekas G, Grindem H, et al. 2018 international olympic committee consensus statement on prevention, diagnosis, and management of pediatric anterior cruciate ligament injuries. Orthop J Sports Med. 2018;6(3):2325967118759953.
9. Greulich WWPS. Radiographic atlas of skeletal development of the hand and wrist. 2nd ed. Stanford: Stanford University Press; 1959.
10. Sanders JO, Khoury JG, Kishan S, et al. Predicting scoliosis progression from skeletal maturity: a simplified classification during adolescence. J Bone Joint Surg Am. 2008;90(3):540–53.

11. Heyworth BE, Osei DA, Fabricant PD, et al. The shorthand bone age assessment: a simpler alternative to current methods. J Pediatr Orthop. 2013;33(5):569–74.
12. Engelman GH, Carry PM, Hitt KG, Polousky JD, Vidal AF. Comparison of allograft versus autograft anterior cruciate ligament reconstruction graft survival in an active adolescent cohort. Am J Sports Med. 2014;42(10):2311–8.
13. Kaeding CC, Aros B, Pedroza A, et al. Allograft versus autograft anterior cruciate ligament reconstruction: predictors of failure from a MOON prospective longitudinal cohort. Sports Health. 2011;3(1):73–81.
14. Kocher MS, Micheli LJ, Zurakowski D, Luke A. Partial tears of the anterior cruciate ligament in children and adolescents. Am J Sports Med. 2002;30(5):697–703.
15. Lang PJ, Sugimoto D, Micheli LJ. Prevention, treatment, and rehabilitation of anterior cruciate ligament injuries in children. Open Access J Sports Med. 2017;8:133–41.
16. Milewski MD, Beck NA, Lawrence JT, Ganley TJ. Anterior cruciate ligament reconstruction in the young athlete: a treatment algorithm for the skeletally immature. Clin Sports Med. 2011;30(4):801–10.
17. Kocher MS, Garg S, Micheli LJ. Physeal sparing reconstruction of the anterior cruciate ligament in skeletally immature prepubescent children and adolescents. J Bone Joint Surg Am. 2005;87(11):2371–9.
18. Kocher MS, Heyworth BE, Fabricant PD, Tepolt FA, Micheli LJ. Outcomes of physeal-sparing ACL reconstruction with iliotibial band autograft in skeletally immature prepubescent children. J Bone Joint Surg Am. 2018;100(13):1087–94.
19. Anderson AF. Transepiphyseal replacement of the anterior cruciate ligament in skeletally immature patients. A preliminary report. J Bone Joint Surg Am. 2003;85-A(7):1255–63.
20. Lawrence JT, Bowers AL, Belding J, Cody SR, Ganley TJ. All-epiphyseal anterior cruciate ligament reconstruction in skeletally immature patients. Clin Orthop Relat Res. 2010;468(7):1971–7.
21. Kruse LM, Gray BL, Wright RW. Anterior cruciate ligament reconstruction rehabilitation in the pediatric population. Clin Sports Med. 2011;30(4):817–24.
22. Kushner AM, Kiefer AW, Lesnick S, Faigenbaum AD, Kashikar-Zuck S, Myer GD. Training the developing brain part II: cognitive considerations for youth instruction and feedback. Curr Sports Med Rep. 2015;14(3):235–43.
23. National Center for Injury Prevention and Control. CDC injury research agenda 2009–2018. http://stacks.cdc.gov/view/cdc/21769. Accessed 20 Oct 2018.
24. Hutchinson AB, Yao P, Hutchinson MR. Single-leg balance and core motor control in children: when does the risk for ACL injury occurs? BMJ Open Sport Exerc Med. 2016;2(1):e000135.
25. Holden S, Boreham C, Doherty C, Wang D, Delahunt E. Clinical assessment of countermovement jump landing kinematics in early adolescence: sex differences and normative values. Clin Biomech (Bristol, Avon). 2015;30(5):469–74.
26. Moksnes H, Engebretsen L, Risberg MA. Management of anterior cruciate ligament injuries in skeletally immature individuals. J Orthop Sports Phys Ther. 2012;42(3):172–83.
27. Moksnes H, Grindem H. Prevention and rehabilitation of paediatric anterior cruciate ligament injuries. Knee Surg Sports Traumatol Arthrosc. 2016;24(3):730–6.
28. Sugimoto D, Heyworth BE, Brodeur JJ, Kramer DE, Kocher MS, Micheli LJ. Effect of graft type on balance and hop tests in adolescent males following anterior cruciate ligament reconstruction. J Sport Rehabil. 2018:1–27. https://doi.org/10.1123/jsr.2017-0244.
29. Yellin JL, Fabricant PD, Gornitzky A, et al. Rehabilitation following anterior cruciate ligament tears in children: a systematic review. JBJS Rev. 2016;4(1). https://doi.org/10.2106/JBJS.RVW.O.00001.
30. Greenberg EM, Greenberg ET, Ganley TJ, Lawrence JT. Strength and functional performance recovery after anterior cruciate ligament reconstruction in preadolescent athletes. Sports Health. 2014;6(4):309–12.
31. Hartigan EH, Axe MJ, Snyder-Mackler L. Time line for noncopers to pass return-to-sports criteria after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2010;40(3):141–54.
32. Wren TAL, Mueske NM, Brophy CH, et al. Hop distance symmetry does not indicate normal landing biomechanics in adolescent athletes with recent anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2018;48(8):622–9.
33. Graziano J, Chiaia T, de Mille P, Nawabi DH, Green DW, Cordasco FA. Return to sport for skeletally immature athletes after ACL reconstruction: preventing a second injury using a quality of movement assessment and quantitative measures to address modifiable risk factors. Orthop J Sports Med. 2017;5(4):2325967117700599.
34. Sterett WI, Briggs KK, Farley T, Steadman JR. Effect of functional bracing on knee injury in skiers with anterior cruciate ligament reconstruction: a prospective cohort study. Am J Sports Med. 2006;34(10):1581–5.
35. Dai B, Butler RJ, Garrett WE, Queen RM. Anterior cruciate ligament reconstruction in adolescent patients: limb asymmetry and functional knee bracing. Am J Sports Med. 2012;40(12):2756–63.
36. Birmingham TB, Bryant DM, Giffin JR, et al. A randomized controlled trial comparing the effectiveness of functional knee brace and neoprene sleeve use after anterior cruciate ligament reconstruction. Am J Sports Med. 2008;36(4):648–55.
37. Albright JC, Crepeau AE. Functional bracing and return to play after anterior cruciate ligament reconstruction in the pediatric and adolescent patient. Clin Sports Med. 2011;30(4):811–5.
38. Padaki AS, Noticewala MS, Levine WN, Ahmad CS, Popkin MK, Popkin CA. Prevalence of posttraumatic stress disorder symptoms among young athletes after

anterior cruciate ligament rupture. Orthop J Sports Med. 2018;6(7):2325967118787159.
39. Paterno MV, Flynn K, Thomas S, Schmitt LC. Self-reported fear predicts functional performance and second ACL injury after ACL reconstruction and return to sport: a pilot study. Sports Health. 2018;10(3):228–33.
40. DiSanti J, Lisee C, Erickson K, Bell D, Shingles M, Kuenze C. Perceptions of rehabilitation and return to sport among high school athletes with ACL reconstruction: a qualitative research study. J Orthop Sports Phys Ther. 2018;48(12):951–9.
41. Coronado RA, Bird ML, Van Hoy EE, Huston LJ, Spindler KP, Archer KR. Do psychosocial interventions improve rehabilitation outcomes after anterior cruciate ligament reconstruction? A systematic review. Clin Rehabil. 2018;32(3):287–98.
42. Hallquist C, Fitzgerald UT, Alricsson M. Responsibility for child and adolescent's psychosocial support associated with severe sports injuries. J Exerc Rehabil. 2016;12(6):589–97.
43. Trentacosta NE, Vitale MA, Ahmad CS. The effects of timing of pediatric knee ligament surgery on short-term academic performance in school-aged athletes. Am J Sports Med. 2009;37(9):1684–91.
44. Dekker TJ, Godin JA, Dale KM, Garrett WE, Taylor DC, Riboh JC. Return to sport after Pediatric anterior cruciate ligament reconstruction and its effect on subsequent anterior cruciate ligament injury. J Bone Joint Surg Am. 2017;99(11):897–904.
45. Kay J, Memon M, Marx RG, Peterson D, Simunovic N, Ayeni OR. Over 90% of children and adolescents return to sport after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Knee Surg Sports Traumatol Arthrosc. 2018;26(4):1019–36.
46. Geffroy L, Lefevre N, Thevenin-Lemoine C, et al. Return to sport and re-tears after anterior cruciate ligament reconstruction in children and adolescents. Orthop Traumatol Surg Res. 2018;104(8S):S183–8.
47. Webster KE, Feller JA, Leigh WB, Richmond AK. Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. Am J Sports Med. 2014;42(3):641–7.
48. Chicorelli AM, Micheli LJ, Kelly M, Zurakowski D, MacDougall R. Return to sport after anterior cruciate ligament reconstruction in the skeletally immature athlete. Clin J Sport Med. 2016;26(4):266–71.
49. Christino MA, Tepolt FA, Sugimoto D, Micheli LJ, Kocher MS. Revision ACL reconstruction in children and adolescents. J Pediatr Orthop. 2018; https://doi.org/10.1097/BPO.0000000000001155.
50. Shea KG, Belzer J, Apel PJ, Nilsson K, Grimm NL, Pfeiffer RP. Volumetric injury of the physis during single-bundle anterior cruciate ligament reconstruction in children: a 3-dimensional study using magnetic resonance imaging. Arthroscopy. 2009;25(12):1415–22.
51. Chotel F, Henry J, Seil R, Chouteau J, Moyen B, Berard J. Growth disturbances without growth arrest after ACL reconstruction in children. Knee Surg Sports Traumatol Arthrosc. 2010;18(11):1496–500.
52. Frosch KH, Stengel D, Brodhun T, et al. Outcomes and risks of operative treatment of rupture of the anterior cruciate ligament in children and adolescents. Arthroscopy. 2010;26(11):1539–50.
53. Huleatt J, Gottschalk M, Fraser K, et al. Risk factors for manipulation under anesthesia and/or lysis of adhesions after anterior cruciate ligament reconstruction. Orthop J Sports Med. 2018;6(9):2325967118794490.
54. Bram JT, Gambone AJ, DeFrancesco CJ, Striano BM, Ganley TJ. Use of continuous passive motion reduces rates of arthrofibrosis after anterior cruciate ligament reconstruction in a pediatric population. Orthopedics. 2019;42(1):e81–5.
55. Fabricant PD, Tepolt FA, Kocher MS. Range of motion improvement following surgical management of knee arthrofibrosis in children and adolescents. J Pediatr Orthop. 2018;38(9):e495–500.
56. Vander Have KL, Ganley TJ, Kocher MS, Price CT, Herrera-Soto JA. Arthrofibrosis after surgical fixation of tibial eminence fractures in children and adolescents. Am J Sports Med. 2010;38(2):298–301.
57. Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med. 2005;33(7):1003–10.
58. Beaudouin F, Rossler R, Aus der Funten K, et al. Effects of the '11+ Kids' injury prevention programme on severe injuries in children's football: a secondary analysis of data from a multicentre cluster-randomised controlled trial. Br J Sports Med. 2018; https://doi.org/10.1136/bjsports-2018-099062.
59. Rossler R, Junge A, Bizzini M, et al. A multinational cluster randomised controlled trial to assess the efficacy of '11+ Kids': a warm-up programme to prevent injuries in children's football. Sports Med. 2018;48(6):1493–504.
60. Magnussen RA, Lawrence JT, West RL, Toth AP, Taylor DC, Garrett WE. Graft size and patient age are predictors of early revision after anterior cruciate ligament reconstruction with hamstring autograft. Arthroscopy. 2012;28(4):526–31.
61. Astur DC, Cachoeira CM, da Silva Vieira T, Debieux P, Kaleka CC, Cohen M. Increased incidence of anterior cruciate ligament revision surgery in paediatric verses adult population. Knee Surg Sports Traumatol Arthrosc. 2018;26(5):1362–6.

27 Return to Sport After Meniscus Operations: Meniscectomy, Repair, and Transplantation

Frank R. Noyes and Sue Barber-Westin

27.1 Introduction

27.1.1 Functions of the Menisci and the Importance of Preservation

The crucial roles of the menisci in the human knee are well understood and include load-bearing, load transmission, shock absorption, and lubrication and nutrition of articular cartilage [1–5]. The menisci act as spacers between the femoral condyles and tibial plateaus and when there are no compressive weight-bearing loads across the joint, limit contact between the articular surfaces. Underweight bearing conditions, the menisci assume a significant load-bearing function in the tibiofemoral joint [6–8]. At least 50% of the compressive load of the knee joint is transmitted through the menisci in 0° of extension, and approximately 85% of the load is transmitted at 90° of flexion [6, 9]. Loss of either meniscus leads to instability, symptoms of pain and swelling, reduction of tibiofemoral joint space, and articular cartilage degeneration [10–16].

The menisci remain in constant congruity with the tibial and femoral articular surfaces throughout knee flexion and extension [17, 18] and contribute to knee joint stability [19, 20]. The presence of intact menisci increases the contact area to 2.5 times the size compared with a meniscectomized joint [21]. The larger contact area provided by the menisci reduces the average contact stress acting between the joint surfaces. Removal of as little as 15–34% of a meniscus increases contact pressures by more than 300% [8, 22]. After total meniscectomy, the tibiofemoral contact area decreases by approximately 50% and the contact forces increase two- to threefold [3, 6, 9, 21, 23–29].

The lateral meniscus provides concavity to the lateral tibiofemoral joint due to the normal posterior convexity of the lateral tibial condyle, allowing the stabilizing effect of joint weight-bearing forces to reduce lateral compartment anterior and posterior translations [30]. Total lateral meniscectomy results in a 50% decrease in the total contact area and a 235–335% increase in peak local contact pressure [9]. Loss of the medial meniscus results in a smaller, more medial displacement of the center of pressure. The load is subsequently transmitted through the articular cartilage and subchondral bone to the underlying cancellous bone through this more central route.

The deleterious effects of meniscectomy on tibiofemoral compartment articular cartilage have been demonstrated in multiple experimental studies [8, 21, 31–34]. In addition, poor long-term clinical results have been reported by many investigators following partial and total

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_27

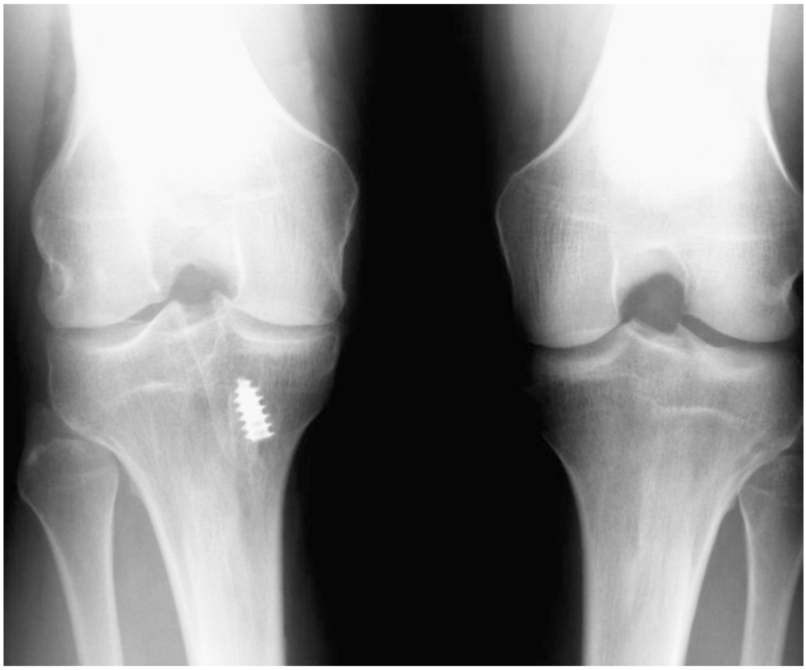


Fig. 27.1 Standing radiographs of a patient 14 years after a right ACL reconstruction and subsequent medial meniscectomy. The pivot-shift test was negative, indicating a stable reconstruction. However, narrowing to the medial tibiofemoral compartment is evident and the patient demonstrated 2° of varus alignment (Reprinted from Noyes and Barber-Westin [51])

meniscectomy [11, 14, 35–43]. Meniscus tears frequently occur simultaneously with anterior cruciate ligament (ACL) ruptures [44–47]. Clinical studies report a higher incidence of lateral meniscus tears than medial meniscus tears in acute ACL-injured knees [46]. However, if the ACL injury is treated conservatively, a higher incidence of secondary medial meniscus tears has been noted [46, 48–50]. Studies have shown that, regardless of the outcome of ACL reconstruction in terms of restoration of knee stability, meniscectomy accelerates degenerative joint changes (Fig. 27.1) [52–59]. Nearly every long-term study has reported a statistically significant correlation between meniscectomy performed either concurrently or after the ACL reconstruction and moderate-to-severe radiographic evidence of OA.

Many types of meniscus tears may be successfully repaired (Fig. 27.2) [51], with well-recognized published success rates that warrant the procedure whenever possible [60–63]. Meniscus tears in the periphery or outer red-red (R/R) region have very high healing rates of ≥95% [64–67] and tears that extend into the central avascular region have acceptable clinical success rates of ≥80% [60, 64, 68]. There are certain tear patterns, such as radial, that have lower success rates due to the lack of vascular supply. We previously described in detail the importance of the operative technique required to obtain a stable and reduced meniscus tear [51]. We prefer an inside-out technique that uses an accessory posteromedial or posterolateral incision and multiple vertical divergent sutures (Fig. 27.3). Biomechanical studies in large animal models demonstrate healing rates ranging from 85% to 93% of meniscus tears repaired with an inside-out technique [70–73]. In cadaver models, suture repair successfully restores joint biomechanics to within normal conditions for posterior root tears [74] and bucket-handle tears [75]. There are certain meniscus tears in which placement of accurate sutures for meniscus repairs can be achieved with modern commercial suture instrumentation (flexible all-inside devices), such as longitudinal tears in the R/R region [76]. We recommend avoiding the use of only 2–3 sutures for all-inside repairs because of the uncertain tensile strength that is required to

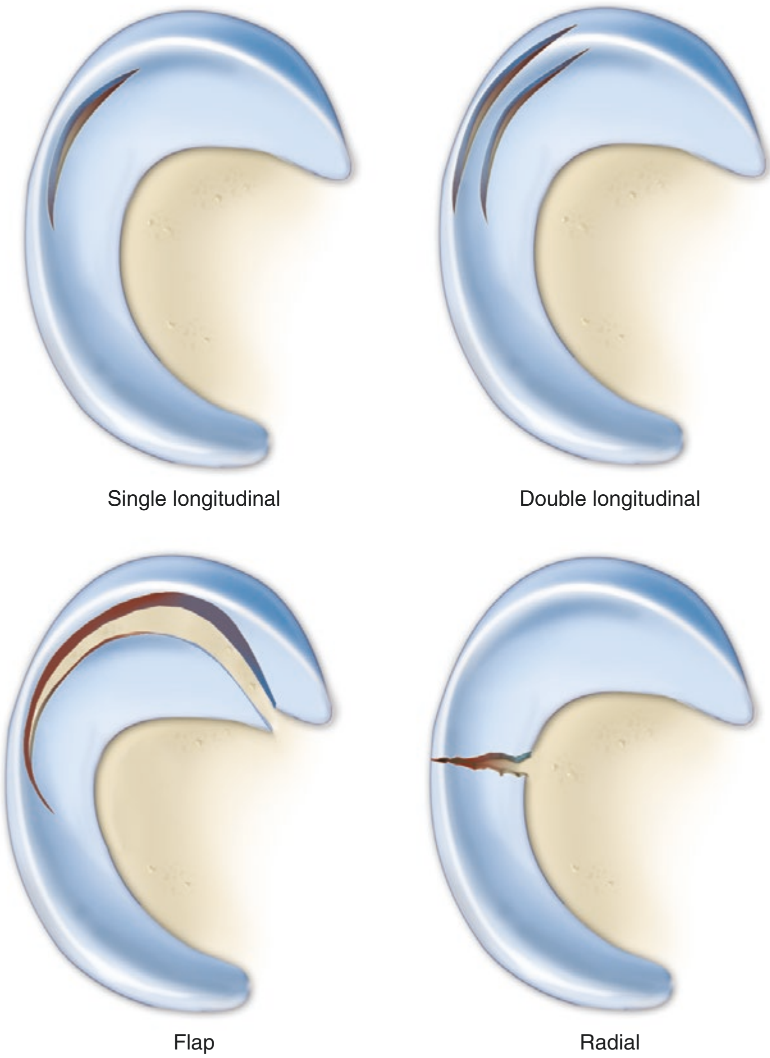


Fig. 27.2 Common complex and avascular meniscus tear patterns. Single longitudinal and radial tears occur in a single plane, while double longitudinal and flap tears occur in multiple planes (Reprinted from Noyes and Barber-Westin [51])

provide stability during early postoperative rehabilitation. Studies reporting cyclic loading of suture repairs compared with all-inside devices report that suture repairs have the higher load-to-failure force and strength properties [77]. We first reported in 1987 that early knee motion and partial weight-bearing was safe and did not disrupt healing meniscus repairs [78]. Subsequent multiple clinical studies from our center [62, 68, 79] and other investigators [80–83] provide clear evidence that these basic rehabilitation procedures are not deleterious and are effective in preventing arthrofibrosis postoperatively.

27.1.2 Options for Treatment of Meniscus Tears in Athletes

The optimal treatment of symptomatic meniscus tears in high-demand athletes is controversial. Although systematic reviews have demonstrated that meniscal repair provides superior results compared with meniscectomy in terms of function with daily activities and radiologic osteoarthritis scores [84, 85], few investigations have focused on return to sport (RTS) activities. One review compared RTS outcomes between partial meniscectomy and meniscus repair in

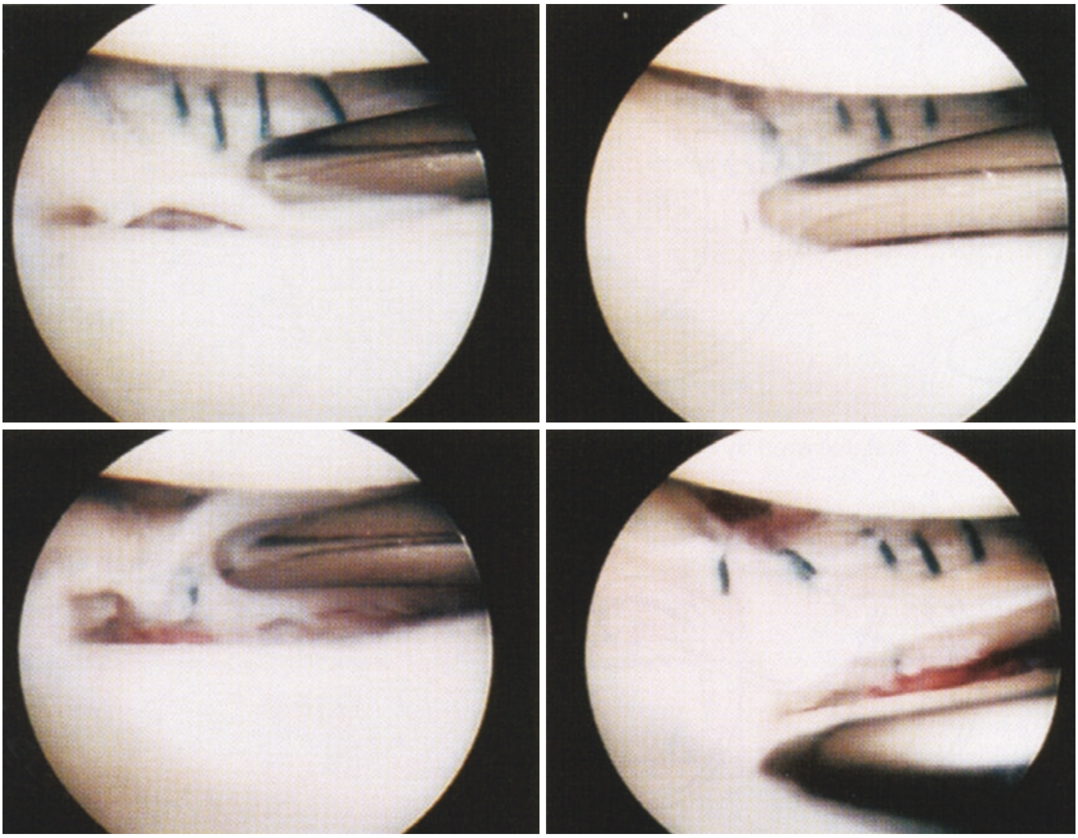


Fig. 27.3 Meniscus repair instead of meniscectomy to preserve knee joint function. A longitudinal meniscal tear site demonstrates some fragmentation inferiorly. This tear required multiple superior and inferior vertical divergent sutures to achieve anatomic reduction (Reprinted from Noyes and Barber-Westin [69])

elite athletes (predominately male), defined as professional or amateur competing on an international level [86]. Six meniscectomy studies (184 patients) and three meniscal repair studies (111 patients) were included and 33% underwent an associated ACL reconstruction. Short-term follow-up (<5 years) was reported in six studies and mid-term results (6–8 years) was provided in three. Overall, 86% of athletes who had meniscal repair RTS at the preinjury level compared with 80% of athletes who had meniscectomy. Data for isolated meniscal surgeries showed 93% RTS after repair and 84% RTS after meniscectomy. Time to RTS was only provided in two meniscal repair studies and varied from 1.1 to 8.5 months. There was no analysis of progression of radiographic knee joint osteoarthritis (OA) or reoperations.

Stein et al. [43] conducted a long-term comparison of outcomes between 42 athletes who underwent isolated meniscus repair and 39 who underwent meniscectomy. Patients were placed into either an athlete or non-athlete subgroup; however, sports activity levels were not detailed. At a mean of 8.8 years postoperatively, 94% in the repair group had returned to the preinjury sports activities compared with 44% in the meniscectomy group ($P = 0.001$). Progression of knee OA was found in 60% in the meniscectomy group compared with 19% of the repair group ($P = 0.005$). The authors also reported a protective effect against progression of knee OA after meniscal repair in patients ≤30 years of age ($P = 0.01$), whereas no such effect was found for patients >30 years of age. The conclusion was reached that meniscal repair resulted in significant benefits for prophylaxis from knee OA and resumption of previous sports activity levels compared with partial meniscectomy.

For certain athletes such as collegiate scholarship candidates and professionals, the decision of whether to undergo meniscus repair and the associated longer rehabilitation period compared with meniscectomy may be difficult. Although meniscectomy would be assumed to allow a faster RTS, the well-known knee joint OA that may occur years later is to be considered. While meniscus repair is theoretically preferred to salvage meniscus tissue, the return to high-loading activities may place these repairs at high risk for failure. At the time of writing, few systematic reviews were available that focused on meniscus repair outcomes in elite athletes. Eberbach et al. [87] assessed isolated meniscus repair RTS outcomes in six studies; two of which involved 21 professional athletes and four that focused on 71 recreational athletes. The investigators reported RTS rates of 86% and 90%, respectively and failure rates of 9% and 22%, respectively. The decision of whether to repair a (correctly indicated) meniscus tear in elite athletes become less complicated when an associated ACL reconstruction is performed because the recovery period will not be impacted by repair of either a simple or complex tear. The same situation exists when the injury occurs very late in the season if the decision is made to forgo the remaining games. The longer recovery period before the next season allows for meniscus repair to be considered.

Recreational athletes with symptomatic meniscus tears must carefully weigh the potential advantages and disadvantages of repair versus meniscectomy. Factors such as age, type, and frequency of sport participation, and associated or pre-existing conditions play important roles in surgical decision-making. It is especially important to preserve meniscal function through repair when associated operative procedures are performed, including ACL reconstruction, articular cartilage restoration, and osteotomy (Fig. 27.4).

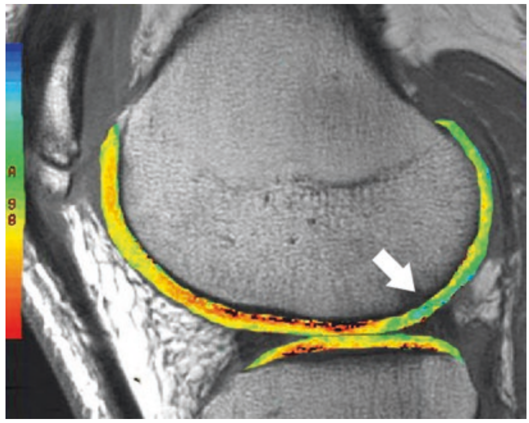


Fig. 27.4 T2 MRI of a 37-year old male 17 years post-ACL reconstruction and lateral meniscus repair. The patient was asymptomatic with light sports activities. The lateral meniscus repair healed and the ACL reconstruction restored normal stability. Prolongation of T2 values is noted over the posterior margin with adjacent subchondral sclerosis (*arrow*) (Reprinted from Noyes et al. [62])

Optimal treatment of symptomatic meniscus tears in children and adolescent athletes should take concerns for the development of future knee joint OA as the primary consideration for the appropriate treatment option. The loss of substantial meniscus tissue in very young athletes may lead to devastating consequences and the need for meniscus transplantation often, in our experience, before the age of 30. Studies of repair of complex tears that extend into the avascular region have success rates that validate this operation in young individuals. Mosich et al. [88] recently reviewed literature on the treatment of isolated meniscus tears in adolescents and reported a shift toward meniscus repair instead of meniscectomy. In 2002, we reported the initial results of a prospective study of the results of repair of meniscus tears that extended into the red/white (R/W) region in patients ≤19 years of age [69]. At a mean of 4.2 years postoperatively, 75% of the repairs were considered clinically successful and 87% of the patients rated their knee as normal or very good.

Meniscus transplantation is an acceptable procedure in younger patients (<50 years of age) in whom the previous meniscectomy has been done and in whom symptoms occur with daily or recreational activities (Fig. 27.5) [89,

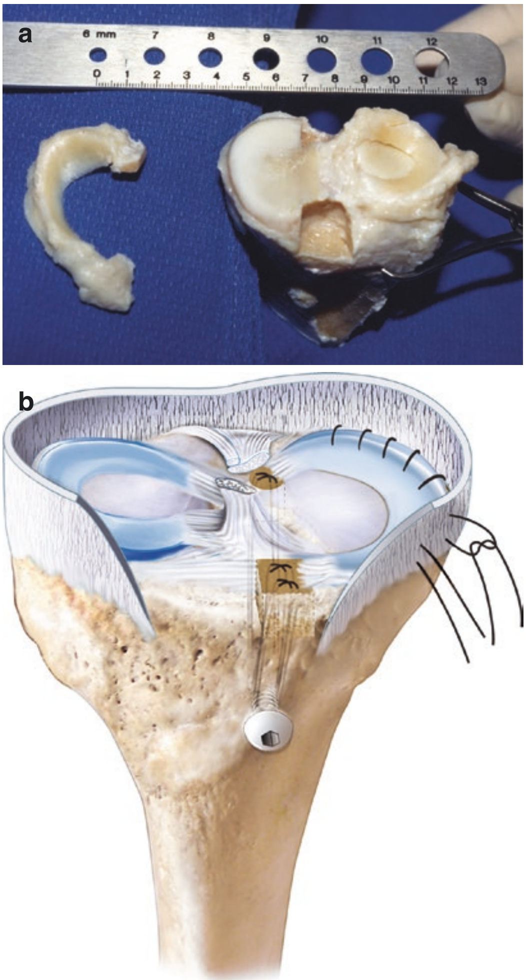


Fig. 27.5 (**a**) Visual inspection of a meniscus transplant before implantation. (**b**) Illustration of medial meniscus transplant with anterior and posterior tunnel fixation and vertical divergent sutures used to secure the meniscus to the capsular attachments (Reprinted from Noyes and Barber-Westin [89])

90]. The majority of studies support the return to an active lifestyle after surgery, but recommend low-impact activities only and not contact sports or those that require extensive twisting, turning, pivoting, and cutting [91]. Rehabilitation requires a minimum of 9 months to prepare for sport-specific training and most authors recommend waiting at least 1 year before participation in athletics [90, 92]. This procedure provides the ability for patients to resume an active lifestyle, including bicycling, swimming, low-impact aerobics, and fitness training.

27.2 Return to Sport After Meniscectomy

Our review of the modern literature found 15 relevant meniscectomy studies (Table 27.1): 6 focused solely on elite and professional athletes [93–98]; 1 included elite, competitive, and recreational athletes [99]; and 8 contained athletes of varying levels (mixed) or in whom activity levels were not defined [35, 40, 43, 100–104] (Tables 27.2 and 27.3). All but two studies (in professional athletes) included only patients with isolated meniscectomy (partial or total). There were 323 professional/elite athletes and 432 other athletes/patients; some studies included both sedentary patients and athletes but did not provide the numbers according to activity levels (Table 27.3). Postoperative follow-up was ≤2 years in 5 studies, 3–5 years in 3 studies, and 6–14 years in 5 studies.

Table 27.1 Summary of studies reviewed

	All studies reviewed		RTS incidence rate		Tegner scores only		Failure data		Knee OA data	
	No. of studies	No. of patients	No of studies	No. of patients	No. of studies	No. of patients	No. of studies	No. of patients	No. of studies	No. of patients
Meniscectomy	15	755	9	463	6	292	NA	NA	9	396
Meniscus repair	25	948	12	395	13	538	25	948	4	258
Meniscus transplantation	18	1052	7	285	11	767	16	892	7	324

NA not available, *OA* osteoarthritis, *RTS* return to sport

Table 27.2 RTS after meniscectomy

Study	Cohort			Operative details, associated procedures	Sports scale (preinjury sports)	RTS data				Osteoarthritis data
	No. men, women	Mean age (range)	Mean follow-up year			Rehab criteria	RTS %	Mean time RTS	Comments	
Minhas et al. [96]	54, 0	26.5 (NP)	2	Isolated meniscectomy	All NBA players	NP	81.5% preinjury	NP	Significantly fewer games played compared with preinjury for post-surgery seasons 1 and 3, but no difference in performance-based outcomes	NP
Aune et al. [93]	72, 0	26.6 (NP)	4.5	Partial LM, ACL-R (51%), microfracture (17%)	All NFL players	NP	61% preinjury	8.5 months all players (following season)	Players drafted in first 4 rounds of NFL draft more likely to RTS (OR 3.7, $P = 0.01$). Players in non-speed positions more likely to return than those in speed positions (OR 4.0, $P = 0.01$). Age, games and seasons played before injury, concomitant procedure, concomitant ACL-R no effect on RTS	NP
Brophy et al. [94]	94, 0	NP	NP	Isolated meniscectomy (57%), meniscectomy and ACL-R (12%), ACL-R only (31%)	All NFL players	NP	(All had to return to meet study inclusionary criteria)	NP	Isolated meniscectomy shorter career length compared with controls (5.6 years vs. 7.0 years; $P < 0.05$); fewer games played (62 vs. 85, $P < 0.05$). Combined meniscectomy-ACL-R no effect career length, games played compared with controls	NP
Nawabi et al. [97]	90, 0	~23 (NP)	NP	Isolated partial MM, LM	All professional soccer players	NP	NP	LM 7 weeks (5–18) MM 5 weeks (3–6) ($P < 0.001$)	Cumulative probability RTS 6 x greater MM than LM ($P < 0.001$). More adverse events after LM than MM (69% vs. 8%; $P < 0.001$). No long-term career length data collected	NP

(continued)

Table 27.2 (continued)

Study	Cohort			Operative details, associated procedures	Sports scale (preinjury sports)	RTS data				Osteoarthritis data
	No. men, women	Mean age (range)	Mean follow-up year			Rehab criteria	RTS %	Mean time RTS	Comments	
Sonnery-Cottet et al. [98]	7, 1	25 (20–32)	6.8	Isolated partial LM followed by rapid chondrolysis	All professional athletes	NP	100% preinjury any time, 75% at latest f.u.	8 months	2 patients retired at 3 and 8 years postop, 6 still playing at latest f.u.	90% grade III-IV Kellgren-Lawrence joint space narrowing
Mariani et al. [105]	5, 0	26.8 (22–34)	2.3	Isolated partial LM followed by rapid chondrolysis	All professional athletes	NP	100% preinjury	4.5 months	All playing without problems	NP
Kim et al. [99]	45, 11	26.7 (13–67)	0.08 (when patients RTS)	Isolated LM, MM	Tegner; 21% elite (mean score 9.3), 41% competitive (mean score 8.3), 38% recreational (mean score 6.6)	Running 4 wks p.o.; full sports activity resumed if possible	(All had to return to meet study inclusionary criteria)	Elite 1.8 months, competitive 1.7 months, recreational 2.9 months ($P < 0.01$)	Patients <30 years age RTS earlier than ≥30 years (1.8 vs. 2.9 months; $P = 0.001$); LM RTS earlier than MM (2 vs. 2.6 months; $P = 0.02$). Pain/effusion upon RTS occurred in 53% LM, 22% MM	NP
Stein et al. [43]	27, 12	32.5 (NP)	8.8	All isolated partial MM	Tegner, mean 6.2	4 weeks p.o.	44% preinjury level. Tegner mean 5.3	NP	Significantly lower percent RTS than meniscus repair group ($P = 0.001$)	Deterioration 60% (1 grade Fairbanks)
Hulet et al. [102]	46, 11	36 (NP)	5 and 12	All isolated partial MM	No scale. 57% participated in sports, 43% pivot and contact sports	NP	5 years: 51% preinjury level 12 years: 24% strenuous activities, 26% moderate activities	NP	Reduction in sports due to personal reasons	19% IKDC grade C, 2% IKDC grade D

ACL anterior cruciate ligament, *ACL-R* anterior cruciate ligament reconstruction, *FU* follow-up, *IKDC* International Knee Documentation Committee, *LM* lateral meniscectomy, *MM* medial meniscectomy, *NBA* National Basketball Association, *NFL* National Football League, *NP* not provided, *RTS* return to sport

Table 27.3 Studies reporting Tegner scores only after meniscectomy

Study	Cohort			Operative details, associated procedures	RTS data				Osteoarthritis data[a]
	No. of men, women	Mean age (range)	Mean follow-up year		Rehab criteria	Mean time RTS	Tegner preop	Tegner FU	
Andersson-Molina et al. [35]	36, 0	28 (16–38)	14	All isolated partial or total LM or MM	NP	NP	7 (MM and LM) All combined: 64% levels 7–10, 30% levels 4–6, 5% levels 0–3	5 (MM and LM) All combined: 25% levels 7–10, 55% levels 4–6, 19% levels 0–3	Fairbanks changes and joint narrowing: partial meniscectomy 33%, total meniscectomy: 72%
Bonneux and Vandekerckhove [100]	20, 9	25 (NP)	8	All isolated partial or subtotal LM	NP	NP	7.2 ± 1.9	5.7 ± 1.8	Fairbanks changes 93%
Rockborn and Messner [40]	Total 30	26 (NP)	1	All isolated partial or subtotal	NP	NP	50% levels 7–10, 27% levels 4–6, 23% levels 0–3	18% levels 7–10, 45% levels 4–6, 36% levels 0–3	Grade 1–2 arthrosis changes 50%
Herrlin et al. [101]	28, 19	54 (45–64)	5	All isolated partial MM	NP	NP	3	3	NP
Yim et al. [104]	9, 41	54 (43–62)	2	All isolated partial MM	NP	NP	4.2	5.1	Minimal changes
Kim et al. [103]	79, 21	Age 40 (all <45)	1.6	All isolated partial MM	3 months	NP	3	5	None

FU follow-up, *IKDC* International Knee Documentation Committee, *LM* lateral meniscectomy, *MM* medial meniscectomy, *NP* not provided

27.2.1 RTS Rates and Influential Factors

The percent of patients who RTS after meniscectomy, reported in six studies, ranged widely from 44% to 100% (Fig. 27.6). In two studies [94, 99], patients were only included if they returned to preinjury level of sport. Brophy et al. [94] reported on 94 National Football League players who underwent either isolated meniscectomy (57%), meniscectomy and ACL reconstruction (12%), or isolated ACL reconstruction (31%). Patients who underwent isolated meniscectomy had shorter average career lengths compared with controls (5.6 and 7.9 years, respectively; $P < 0.05$) and played in fewer games (62 and 85, respectively; $P < 0.05$). Athletes who underwent ACL reconstruction combined with meniscectomy also had a shorter career in terms of years and games played compared with controls, but the difference was not significant in the small cohort of 11 players. Kim et al. [99] reported on a group of 56 athletes classified as either elite (21%), competitive (41%), or recreational (38%). The effect of age and side of meniscectomy on time to RTS was assessed. Patients <30 years of age RTS earlier than those ≥30 (1.8 and 2.9 months, respectively; $P = 0.001$) and patients who had lateral meniscectomy returned earlier than those who had medial meniscectomy (2.0 and 2.6 months, respectively, $P = 0.02$). Pain and/or joint effusion were experienced upon RTS in 53% after lateral meniscectomy and 22% after medial meniscectomy.

Nawabi et al. [97] reported in 90 professional soccer players that the cumulative probability of returning to soccer was nearly six times greater after isolated partial medial meniscectomy compared with lateral meniscectomy ($P < 0.001$). Athletes who underwent lateral meniscectomy experienced more adverse events related to pain and swelling (69% versus 8%, $P < 0.001$). The actual rate of players that returned to preinjury soccer was not provided.

The mean time to RTS was reported in five studies and varied from 1 to 8.5 months postoperatively. In the professional athlete studies, many patients did not return to league competition until the season after the injury, which most likely negatively biased these results. Six studies provided mean Tegner activity level ratings, but no other sport-related data (Table 27.3).

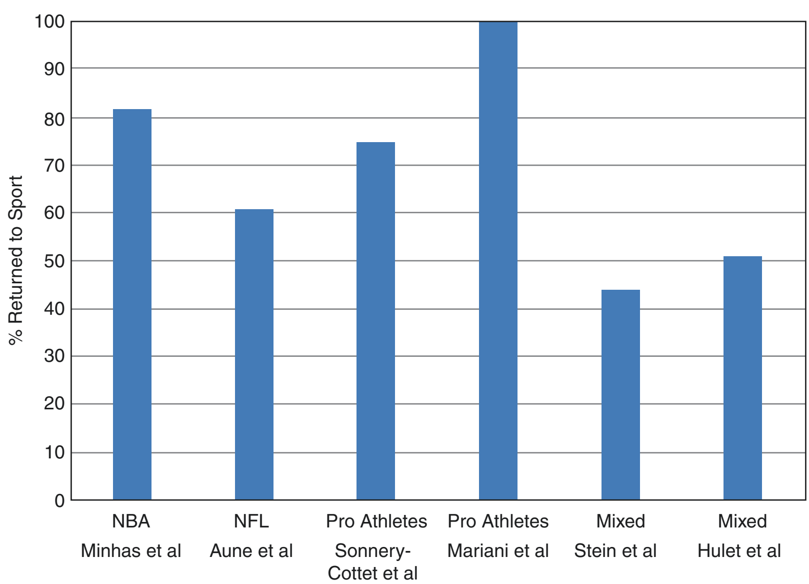


Fig. 27.6 Percentages of athletes who returned to play after partial or total meniscectomy

27.2.2 Rehabilitation Criteria for RTS

None of the 15 studies mentioned objective measures in the rehabilitation program to determine when athletic activities could be resumed postoperatively. One investigation [99] allowed running to begin 4 weeks postoperatively and resumption of full sports when possible. Two studies [43, 103] only provided a time postoperative of when sports resumption was allowed, which ranged from 4 weeks to 3 months.

27.2.3 Progression of Knee Osteoarthritis

Radiographic knee joint OA progression was reported in nine investigations in 396 patients. Bonneux and Vandekerckhove [100] reported Fairbank changes in 93% of 31 patients evaluated a mean of 8 years after partial lateral meniscectomy. Andersson-Molina et al. [35] followed 36 male patients a mean of 14 years following meniscectomy. Fairbank changes and joint narrowing were present in 33% after partial meniscectomy and 72% after total meniscectomy. Stein et al. [43] detected OA progression in 60% of 20 patients who underwent meniscectomy a mean of 9 years previously, which was significantly greater compared with 19% of OA noted in 26 patients who had meniscal repair a mean of 8.6 years previously ($P = 0.005$). Rockborn and Messner [40] followed 30 patients who underwent meniscectomy for 13 years and reported radiographic OA changes in 50%. Hulet et al. [102] conducted a long-term investigation of 74 partial medial meniscectomies in 57 patients with stable knees. At a mean of 12 years postoperatively, joint space narrowing was found in 21%. In patients with a normal contralateral knee, joint space narrowing was noted in 16% of the operated knees. Sonnery-Cottet et al. [98] followed nine cases complicated by the development of rapid chondrolysis after partial lateral meniscectomy for a mean of 6.8 years and reported 90% had Kellgren-Lawrence (K-L) grade III or IV narrowing.

27.3 Return to Sport After Meniscus Repair

Our review of the modern literature found 25 relevant meniscus repair studies involving 948 patients (Table 27.1). Twelve studies [43, 62, 63, 69, 79, 82, 106–112] provided RTS percentage rates (Table 27.4) and 13 others [63, 113–124] reported only mean Tegner scores before and after surgery (Table 27.5). Most studies followed athletes of varying activity levels, although one focused on professional athletes, one on elite athletes (professional, semiprofessional, or amateurs competing at state, national, or international level), and one on high-level soccer players (Tegner levels 9–10). The mean age in 17 studies that included athletes of all ages was approximately 29 years (range, 13–63), and the mean age of eight studies of children and adolescents was approximately 15 years (range, 4–19). Short-term follow-up (<5 years) was provided in 17 studies, mid-term (6–8.5 years) in four studies, and long-term (8.8–16.8 years) in four studies.

27.3.1 RTS Rates and Influential Factors

The percentage of patients who returned to preinjury sports levels, determined in seven studies, ranged from 28% to 95% (Fig. 27.7). Alvarez-Diaz et al. [106] followed 29 male high-level soccer players (Tegner levels 9–10) who underwent all-inside repair of longitudinal meniscus tears; concomitant ACL-reconstruction was performed in 52%. After recovery from surgery, 90% returned to the same level of competitive soccer. At final follow-up, a mean of 6 years postoperatively, 45% were still participating in soccer, although only 28% at the preinjury level. Patients had decreased their level of activity due to occupational or personal reasons and not because of knee-related symptoms. Stein et al. [43] reported that 94% of 42 patients who underwent isolated meniscal repair returned to preinjury activity levels at long-term follow-up

Table 27.4 RTS after meniscus repair

Study	Cohort			Operative details, associated procedures	Sports scale (preinjury sports)	RTS data				Failures (%)
	No. of men, women	Mean age (range)	Mean follow-up year			Rehab criteria	RTS %	Mean time RTS	Comments	
Tucciarone et al. [112]	32, 8	20 (14–26)	2	All-inside R/R (34), R/W (6), FasT-Fix. ACL-R (50%)	Professional athletes	NP	90% any sport	NP	NP	7
Logan et al. [109]	29, 13	23 (15–38)	8.5	Inside-out, all types of repairs ACL-R (83%)	No scale. Elite athletes (rugby, netball, basketball, soccer, other)	NP	81% any sport	5.6 months isolated, 11.8 months ACL-R	19% no return preinjury due to fear reinjury	27
Alvarez-Diaz et al. [106]	29, 0	27 (18–37)	6	All-inside longitudinal posterior horn, FasT-Fix ACL-R (52%)	Tegner 9–10, all soccer players	No inflammation, full knee motion, adequate muscle strength	90% preinjury after surgery; 28% preinjury most recent f.u.	4.3 months isolated, NP ACL-R	45% playing soccer most recent f.u., 17% at lower level No difference RTS rates isolated repair vs. associated ACL-R. Decrease in activity level due to personal or occupational demands	7
Stein et al. [43]	26, 16	31.3 (NP)	8.8	Inside-out R/R or R/W. All isolated	Tegner, mean 5.5, athletes various levels	NP	94% preinjury level; Tegner mean 5.5	NP	Significantly greater percentage RTS compared with meniscectomy group ($P = 0.001$)	14
Imade et al. [107]	9, 6	27 (13–42)	3.4	All revision repairs, R/R (6), R/W (9). All isolated	Tegner, athletes various levels	NP	73% preinjury; 40% preinjury most recent f.u.; 60% lower level	NP	5/11 that resumed preinjury levels sustained retears	33

Noyes and Barber-Westin [79]	23, 6	45 (40–58)	2.8	Inside-out, R/R and R/W ACL-R (72%)	Cincinnati Sports Activity, athletes various levels	Squatting, deep-flexion activities, running, jumping, cutting, twisting restricted for 6 months	76% any sport	NP	72% playing with no symptoms or limitations, 4% playing with symptoms, 20% no sports due to knee, 4% no sports non-knee-related reasons	13
Pujol et al. [110]	13, 6	25 (16–44)	3.3	Open, horizontal. All isolated	No scale, athletes various levels	6 months	95% preinjury	10 months	Sports levels not defined, no rating system	20
Kraus et al. [108]	13, 12	15 (4–17)	2.3	All-inside, R/R, R/W, W/W, inside-out majority ACL-R (44%)	Tegner, children/ adolescents	4–6 months depending on whether ACL-R was done	56% preinjury, Tegner mean 7.2	NP	44% returned lower level. Reduction sports due to fear of reinjury	17
Schmitt et al. [111]	12, 7	14.8 (9–16)	6.1	All-inside FasT-Fix. ACL-R (58%)	Tegner, children/ adolescents	NP	68% preinjury or higher, Tegner mean 7.3	NP	27% returned lower level	10.5
Vanderhave et al. [82]	31, 14	13.2 (9–17)	2.2	Inside-out, R/R (7), R/W (33), W/W/ (9) ACL-R (69%)	Tegner and IKDC, children/ adolescents	4 months isolated, 6 months ACL-R based on clinical progress	88% preinjury, IKDC levels 1 or 2	5.6 months isolated, 8.2 months ACL-R	No difference IKDC levels meniscus repair alone vs. concomitant ACL-R	4
Noyes and Barber-Westin [69]	36, 25	16 (9–19)	4.2	Inside-out R/W, all types ACL-R (61%)	Cincinnati Sports Activity, children/ adolescents	Squatting, deep-flexion activities, running, jumping, cutting, twisting restricted for 6 months	80% any sport	NP	73% no symptoms or limitations, 7% playing with symptoms, 4% no sports due to knee, 16% no sports non-knee-related reasons	25
Noyes et al. [62]	14, 15	16.4 (9.4–20)	16.8	Inside-out R/W, single longitudinal ACL-R (58%)	Cincinnati Sports Activity, children/ adolescents	Squatting, deep-flexion activities, running, jumping, cutting, twisting restricted for 6 months	82% any sport	NP	82% no symptoms or limitation, 18% no sports non-knee-related reasons	38

ACL-R anterior cruciate ligament reconstruction, *FU* follow-up, *IKDC* International Knee Documentation Committee, *R/R* red/red, *RTS* return to sport, *R/W* red/white, *W/W* white/white

Table 27.5 Studies reporting mean Tegner sports scores only after meniscus repair

Study	Cohort			Operative details, associated procedures	RTS data				Failures (%)
	No. of men, women	Mean age (range)	Mean follow-up year		Rehab criteria	Mean time RTS	Tegner preop	Tegner FU	
Barber et al. [115]	25, 11	28 (12–52)	2.5	All-inside longitudinal posterior horn R/R (15), R/W (26), FasT-Fix. Isolated (12), ACL-R (29)	No effusion, full extension, 135° flexion	NP	3.4 (2–6)	7.2 (4–10)	29
Lucas et al. [121]	9, 8	14 (9–18)	1.8	All-inside FasT-Fix or RapidLock, R/R (3), R/W (16). All isolated	6 months	NP	3.9 (3–5)	7.1 (5–9)	30
Ahn et al. [113]	7, 6	20 (14–54)	4	LM bucket handle, all-inside suture or combo outside-in. All isolated	NP	NP	3 (2–6)	7 (4–9)	0
Ahn et al. [114]	23, 9	42 (19–54)	4.1	Horizontal repair, FasT-Fix. All isolated	NP	NP	3.3 (1–5)	6.8 (5–8)	9
Tagliero et al. [63]	17, 30	16.6 (NP)	16.6	Inside-out or all-inside, simple, bucket handle, complex. All with ACL-R	6–9 months	NP	1.9	6.3	28
Krych et al. [119]	43, 56	16 (13–18)	8	Inside-out or all-inside, simple, bucket handle, complex. All with ACL-R	6–9 months when patient regained functional stability	NP	1.9 (0–7)	6.2 (2–10)	26
Chiang et al. [116]	19, 12	30 (18–44)	3	All-inside vertical R/R (18), R/W (13) FasT-Fix. Isolated (18), ACL-R (13)	6 months isolated repair, 9 months ACL-R	NP	3.5 (2–5)	6.2 (5–9)	3
Majewski et al. [122]	54, 34	30 (15–60)	10	Outside-in, longitudinal. All isolated	NP	NP	7 (3–10)	6 (3–10)	24
Stein et al. [124]	10, 5	31 (20–63)	2.5	Inside-out longitudinal or bucket handle. All isolated	NP	NP	6.3 All recreational or competitive athletes 5 ×/week	5.9	0
Choi et al. [117]	11, 3	30 (16–52)	3	All-inside LM radial tears R/R, R/W. All isolated	After 6 months	NP	4 (1–8)	5.7 (3–7)	21
Kotsovolos et al. [118]	37, 21	32 (16–54)	1.5	All-inside R/R (22), R/W (39), FasT-Fix. Isolated (19), ACL-R (39)	5 months	NP	3.2 (2–5)	5.7 (5–8)	10
Martin-Fuentes et al. [123]	33, 10	31 (17–47)	~3	All-inside FasT-Fix, R/R (35), R/W (10). Isolated (19), ACL-R (24)	6 months isolated, 9 months ACL-R	NP	2.9 (1–4)	5.5 (3–7)	14
Lind et al. [120]	41, 19	NP (18–50)	2	All-inside, FasT-Fix or arrow. All isolated	4–6 months	NP	4.2	4.5	39

ACL-R anterior cruciate ligament reconstruction, *F* female, *FU* follow-up, *LM* lateral meniscus, *M* male, *MM* medial meniscus, *NP* not provided, *R/R* red/red, *RTS* return to sport, *R/W* red/white

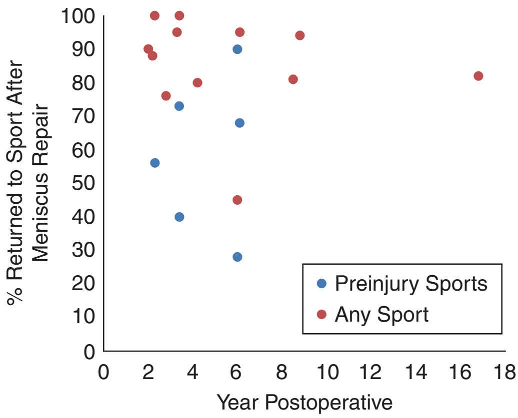


Fig. 27.7 The percent of patients who returned to either preinjury sports activities and/or any sport after meniscus repair

(5–8 years), compared with 44% of 39 patients who underwent meniscectomy ($P = 0.001$).

The percentage of patients that returned to any sports activity, reported in 12 studies, ranged from 45% to 100%. At least 80% of athletes returned to some type of athletic activity in ten studies. There was no significant effect (positive or negative) of a concomitant ACL reconstruction on the outcome in regard to RTS [62, 69, 79, 82, 106, 108, 109, 111, 112], with the exception of an expected longer time for release to unrestricted activities [82, 109]. No other factors that could have affected RTS, such as age, gender, or preinjury activity level, were routinely examined.

Seven studies focused on the outcome of meniscal repair in children and adolescent athletes [82, 108]. Four were short-term investigations (1.8–4.2 years postoperative), 1 mid-term (6.1 years), and 2 long-term (8 and 16.8 years). Only three studies determined return to previous activity levels, which ranged from 56% to 88%. Five studies reported that ≥80% of patients returned to some type of athletic activity.

27.3.2 Rehabilitation Criteria for RTS

Few investigations provided rehabilitation criteria for RTS after meniscus repair performed either in isolation or with an ACL reconstruction (Table 27.6). Postoperative time periods were cited as the only criteria in 11 studies and were provided along with ambiguous criteria such as "based on clinical progress" in three other studies. Our three investigations [62, 69, 79] detailed the program and added the criteria of squatting, deep flexion activities, running, jumping, cutting and twisting restricted for 6 months. In addition, we previously described our postoperative program in detail, including criteria for RTS (Table 27.7) [92].

Table 27.6 Rehabilitation criteria for RTS after meniscus repair

	No. of studies		
Criteria	Isolated repair	Associated ACL-R	Either isolated or with ACL-R
9 months		1	
>6 months	1		
6 months	4	1	
6–9 months		1	
4–6 months	1		
5 months	1		
4 months	1		
4 months based on clinical progress	1		
6 months based on clinical progress		1	
6–9 months and regained functional stability		1	
Squatting, deep-flexion activities, running, jumping, cutting, twisting restricted for 6 months			3
No inflammation, full knee motion, adequate muscle strength			1

ACL-R anterior cruciate ligament reconstruction, *RTS* return to sport

27.3.3 Failure Rates of Meniscus Repairs

All 25 studies reported meniscus repair failure rates; failures were documented in 23 studies and ranged from 4% to 39%. Eight studies cited both reinjuries (usually sustained during sports) and

Table 27.7 Authors' Rehabilitation Criteria for RTS for Meniscus Repairs and Transplants

Activity	Approximate postoperative time period	Criteria to begin
Running program	16–20 weeks peripheral meniscus repairs 30 weeks complex meniscus repairs extending into avascular region 12 months meniscus transplants	Isokinetic test: ≤30% deficit peak torque deficit quadriceps and hamstrings No pain or swelling
Cutting, agility program	>20 weeks peripheral meniscus repairs >35 weeks complex meniscus repairs >12 months meniscus transplants	Successful completion of the running program No pain or swelling
Beginning plyometrics	Usually 6 months peripheral and complex meniscus repairs 9 months radial repairs >1 year meniscus transplants	Successful completion of the running and cutting/agility programs No pain or swelling
Advanced plyometrics (for patients wishing to resume sports involving extensive jumping, cutting, pivoting)	>6 months peripheral and complex meniscus repairs >9 months radial repairs	Successful completion of the beginning plyometrics program No pain or swelling Usually not done in meniscus transplant patients Isokinetic test: ≤10% deficit peak torque deficit quadriceps and hamstrings
Return to sports, no ACL-R	>6 months peripheral and complex meniscus repairs >9 months radial repairs >1 year meniscus transplants (low-impact sports only recommended)	After successful completion of plyometric training and sports-specific functional training No pain or swelling
Return to sports, associated ACL-R	>6 months peripheral and complex meniscus repairs >9 months radial repairs >1 year meniscus transplants (low-impact sports only recommended)	Isokinetic test: ≤10% deficit peak torque deficit quadriceps and hamstrings No pain, swelling, patellofemoral crepitus Lachman, knee arthrometer test: ≤ 3 mm increase opposite side Single-leg hop: ≤15% deficit Video drop-jump test: ≥60% normalized knee separation distance Single-leg squat test: no valgus knee motion or medial-lateral movement of knee on

ACL-R anterior cruciate ligament reconstruction, *RTS* return to sport
From Heckmann et al. [92]

atraumatic reasons for failed meniscus repairs, with the rate of atraumatic failures reported the most frequently (Fig. 27.8). In 15 studies that reported no reinjuries, 13 cited atraumatic failure rates that ranged from 7% to 39%. These failures typically represented persistent symptoms such as pain and locking related to the meniscus repair or were designated according to radiographic or magnetic resonance imaging (MRI) criteria. For instance, we conducted a long-term study (mean, 16.8 years) of single longitudinal meniscus repairs that extended into the central region in patients ≤20 years of age [62]. We found that 62% of the meniscus repairs had normal or nearly normal characteristics, 21% required arthroscopic resection, and 17% had atraumatic failure criteria (loss of joint space on radiographs or MRI criteria). The majority of patients (82%) were participating in sports without problems.

The overall rates of failure of eight studies of children/adolescents compared with those of studies of athletes of all ages are shown in Fig. 27.9. The largest series of patients aged ≤18 years published to date (99 patients) reported an overall clinical success rate of 74% for all meniscus repairs a mean of 8 years postoperatively [119]. All patients underwent concomitant ACL autogenous reconstruction. Sports involving cutting or pivoting were allowed at 6–9 months if the patient had regained functional stability. Eighteen of 25 patients who reinjured the repair meniscus did to while playing a high-demand

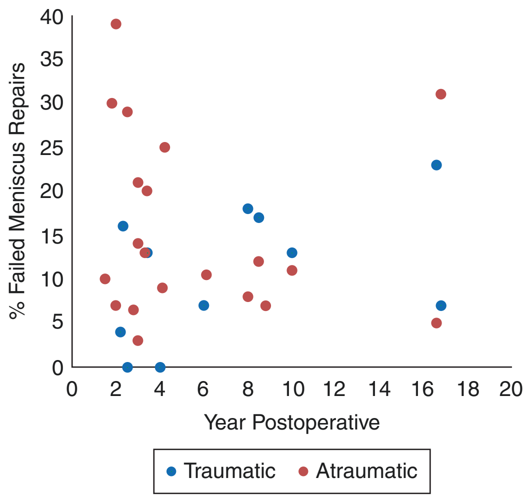


Fig. 27.8 Percentages of failed meniscus repairs resulting from either traumatic reinjuries or atraumatic reasons such as symptoms or signs of tearing/degeneration on MRI

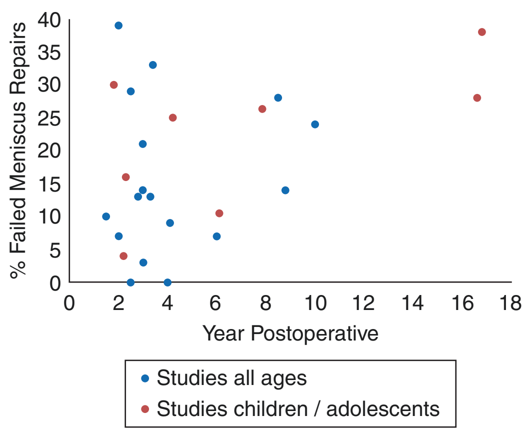


Fig. 27.9 Percentages of failed meniscus repairs in 17 studies that included all ages and eight studies that focused on children/adolescent populations

sport. Higher failure rates were noted in complex and bucket-handle repairs compared with simple ($P = 0.005$ and 0.006, respectively).

27.3.4 Progression of Knee Osteoarthritis

Few studies provided data related to progression of radiographic knee OA after meniscus repair. Stein et al. [43] reported Fairbanks grades of OA in a subgroup of 26 patients (mean age, 31) at midterm (mean, 3.4 years) and long-term (mean, 8.8 years) evaluations. No OA changes were found at midterm and only grade 1 changes were noted in five patients (19%) at long-term. Majewski et al. [122] followed a subgroup of 20 patients (mean age, 30) for 15–17 years postoperatively and reported Fairbanks grade 0 in 25%, grade 1 in 60%, grade 2 in 10%, and grade 3 in 5%. There was no significant difference in the incidence of knee OA compared with that observed at 5–9 years and 10–14 years postoperatively. Two studies determined knee OA in populations of children/adolescents. Krych et al. [119] reported no changes in knee OA in 30 knees (ages 9–18) observed a mean of 4.4 years postoperatively. In our long-term study of 29 knees (mean, 16.8 years), no or only mild joint space narrowing was reported in 89% and severe loss of joint space was found in 11%.

27.4 Return to Sport After Meniscus Transplantation

Our review of the modern literature found 18 relevant meniscus transplantation studies involving 1052 patients. Seven studies [125–130] provided RTS percentage rates (Table 27.8) and 11 others [131–142] reported only mean Tegner scores (Table 27.9). One investigation focused on professional soccer players ($n = 13$), one on competitive soccer players (from low divisions in Spain, $n = 15$), and one on athletes participating in Tegner levels ≥8. The mean age was approximately 33 (range, 6–73). Short-term follow-up (<5 years) was provided in 11 studies, mid-term (5–6 years) in three studies, and long-term (8.6–11.9 years) in four studies.

27.4.1 RTS Rates and Influential Factors

Data from the seven studies that provided RTS percentage rates demonstrated that 71–92% of the patients returned to any sport after meniscus transplantation (Fig. 27.10). Only four studies reported return to preinjury sport rates (in 129 patients) and these varied from 49% to 80%. The

Table 27.8 RTS after meniscus transplantation

Study	Cohort			Operative details, associated procedures	Sports scale (preinjury sports)	RTS data				Failures
	No. of men, women	Mean age (range)	Mean follow-up year			Rehab criteria	RTS %	Mean time RTS	RTS comments	
Alentorn-Geli et al. [125]	Total 15	28 (21–45)	3	FF, no bone. All isolated	None, all competitive soccer players	NP	80% preinjury soccer	7.6 months	None	6.6%
Chalmers et al. [126]	4, 9	19 (17–24)	3.3	FF, bone. Isolated (6), ACL-R (3), osteochondral graft (3), microfracture (1)	Tegner, all athletes (3 high school, 9 collegiate, 1 pro)	NP	77% preinjury level	16.5 months (8–24)	70% returned to "desired level of play", 7% returned lower level sport. Mean Tegner 9	23%
Noyes et al. [127]	20, 18	30 (14–49)	3.3	Cryopreserved, bone. Isolated (13), OAT (16), ACL-R (4)	Cincinnati Sports Activity Scale	≥ 1 year, advised no return high-impact sports	76% any sport	NP	Sports: low-impact 63%, running 10%, pivoting/cutting 3%; 3% were participating with symptoms	28%
Marcacci et al. [128]	12, 0	24.5 (19–29)	3	FF, no bone. Isolated (10), ACL-R (2)	Tegner, all male professional soccer players	NP	75% preinjury soccer, mean Tegner 9.2	10.5 months (6.7–15.7)	17% returned semiprofessional level	8%
Stone et al. [131]	36, 13	45 (14–73)	8.6	FF or cryopreserved, bone fixation LM, soft tissue MM. Microfracture (11), cartilage paste graft (10), microfx & paste graft (13); staged cartilage repair (11)	Tegner, all ≥8 before injury	NP	73% any sport	NP	No effect age, time from injury to surgery, or side of transplant on RTS	22%
Noyes and Barber-Westin [129]	33, 36	30 (14–49)	11.9	Cryopreserved, bone. Isolated (32), concurrent/staged procedures (40)	Cincinnati Sports Activity Scale	≥ 1 year, advised no return high-impact sports	71% any sport	NP	Returned to mostly low-impact sports; 5 (7%) were participating with symptoms.	54% Survivorship: 69% at 7 years, 45% at 10 years
Zaffagnini et al. [130]	74, 15	38.5 (16–68)	4.2	FF, nonirradiated, no bone. Isolated (48), ACL-R (11), osteotomy (16), microfracture (9)	Tegner 28% competitive, 72% recreational	NP	49% preinjury level, 25% lower level	8.6 months; 29% returned >12 months	Median Tegner 4. No effect age, gender, side of transplant, BMI, concomitant procedure on RTS	4%

ACL-R anterior cruciate ligament reconstruction, *FF* fresh-frozen, *FU* follow-up, *LM* lateral meniscus, *MM* medial meniscus, *NP* not provided, *OAT* osteochondral autograft transfer, *PCL-R* posterior cruciate ligament reconstruction, *RTS* return to sport

Table 27.9 Studies reporting mean Tegner sports scores only after meniscus transplantation

Study	Cohort			Operative details, associated procedures	RTS data				Failures
	No. of men, women	Mean age (range)	Mean follow-up year		Rehab criteria	Mean time RTS	Tegner preop mean	Tegner FU mean	
Vundelinckx et al. [139]	18, 16	33 (14–47)	8.8	Cryopreserved, no bone. Isolated (30), osteotomy (3), microfracture (2)	NP	NP	3.6	3.2	14%
Mahmoud et al. [136]	Total 30	34.9 (NP)	9.8	Bone fixation. Isolated (15), ACL-R (5), PCL-R (2), osteotomy (6), chondral repair (2)	≥ 1 year, advised no return high-impact sports	NP	3.0	3.6	18%
Stone et al. [138]	83, 32	46.9 (14–73)	5.8	FF or cryopreserved, bone fixation LM, soft tissue MM. Osteotomy (15), microfracture (69), cartilage paste graft (67), ACL-R (17)	NP	NP	0.4	3.9	20%
Kempshall et al. [134]	71, 28	NP (16–49)	2.9	Soft tissue fixation. Osteotomy (21), ACL-R (6), microfracture (2)	NP	NP	2	4	20%
Zaffagnini et al. [142]	117, 30	40.9 (16–68)	4.0	FF, soft tissue fixation. Isolated (77), variety concomitant ops (48)	No high demanding sports activities before 8 months	NP	2	4	16%
Yoon et al. [140]	71, 20	32 (18–51)	3.3	FF, bone fixation. Isolated (33), variety concomitant ops (58)	NP	NP	2.4	4.2	NP
Yoon et al. [141]	23, 13	35 (NP)	3.2	FF, bone fixation. All isolated.	NP	NP	3.0	4.3	5%
Lee et al. [135]	28, 21	24.7 (6–49)	3	FF, bone fixation. All isolated	Advised no return high-impact sports	NP	4.7	4.4	NP
Marcacci et al. [137]	23, 9	35 (15–55)	3.3	FF, soft tissue fixation. Isolated (22), ACL-R (4), osteotomy (6)	Advised no return contact sports until 8 months	NP	3	5	6%
Gonzalez-Lucena et al. [133]	24, 9	38 (21–54)	6.5	FF, soft tissue fixation. ACL-R (8), microfracture (8)	Running by sixth months based on patient compliance	NP	3.1	5.5	9%
Abat et al. [132]	56, 32	37 (15–51)	5	FF, bone fixation (55), soft tissue fixation (33). ACL-R (18), microfracture (15)	NP	NP	3	6	8%

ACL-R anterior cruciate ligament reconstruction, *FF* fresh-frozen, *FU* follow-up, *LM* lateral meniscus, *MM* medial meniscus, *NP* not provided, *PCL-R* posterior cruciate ligament reconstruction, *RTS* return to sport

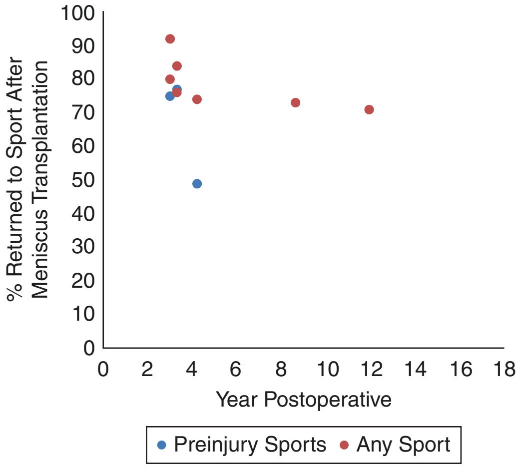


Fig. 27.10 Data from seven studies that followed 236 athletes are shown regarding the percent who returned to either preinjury sports activities and/or any sport after meniscus transplantation

largest series was reported by Zaffagnini et al. [130] who followed 89 patients (mean age, 38.5 years) who were all active athletes, with the level of preinjury activity designated as competitive in 28% and recreational in 72%. The patients were followed a mean of 4.2 years postoperatively, at which time 49% had returned to their preinjury level and 74% had returned to some type of sport. The mean time to RTS was 8.6 months; nearly one-third of the patients returned after 1 year postoperatively. There was no effect of age, gender, side of transplant, time from meniscectomy, body mass index, or concomitant procedures on RTS incidence rates. We reported long-term survivorship rates in 69 meniscus transplants a mean of 11.9 years postoperatively and the functional outcome in 58 of these patients in whom the transplant had survived [129]. Seventy percent were participating in mostly low-impact sports activities without problems and 7% were participating with symptoms. Stone et al. [131] followed 49 competitive athletes with a minimum Tegner score of 8 for a mean of 8.6 years after surgery and reported that 73% returned to some type of sport. There was no effect of age, time from injury to surgery, or side of transplant on RTS. Mean follow-up Tegner scores in the 11 studies shown in Table 27.9 were low, ranging from 3.2 to 6.

27.4.2 Rehabilitation Criteria for RTS

No study provided specific criteria for RTS; however, four investigations advised the return to low-impact activities only [127, 129, 135, 136]. Two other studies [137, 142] advised against returning to high-demand or contact sports until at least 8 months postoperatively. We previously described our postoperative program in detail, including criteria for RTS (Table 27.7) [92].

27.4.3 Failure Rates of Meniscus Transplants

Failure rates of transplants were given or calculated by us for 16 studies (Fig. 27.11). Short-term data (<5 years) was provided in ten investigations, mid-term in 6, and long-term (>10 years) in 1. Our long-term investigation estimated the probability of survival rates of 69 meniscus transplants was 85% at 2 years, 77% at 5 years, 69% at 7 years, and 45% at 10 years [129]. In Stone et al.'s series [131] of 49 competitive athletes, 22% failed an average of 5.2 years postoperatively. There appeared to be no effect of the highest postoperative Tegner score on the failure rate. Chalmers et al. [126] followed 13 patients who participated in either high school, collegiate, or professional athletics before their injury a mean of 3.3 years post-transplantation. The patients all expressed the desire to return to their preinjury activity level and 77% did so a mean of 16.5 months (range, 8–24) postoperatively. Three (23%) failed and required further surgery.

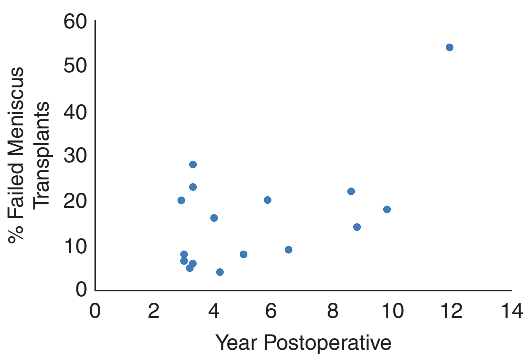


Fig. 27.11 Percentages of failed meniscus transplants in 16 studies

27.4.4 Progression of Knee Osteoarthritis

Only seven studies [126, 127, 129, 132, 133, 135, 139] determined radiographic progression of knee OA and the results varied widely. Abat et al. [132] followed 88 patients a mean of 5 years postoperatively and Gonzalez-Lucena et al. [133] followed 33 patients a mean of 6.5 years postoperatively and both studies reported no increase in knee OA (joint space narrowing, Fairbanks changes). The series of Vundelinckx et al. [139] of 34 patients reported that 42% had increased knee joint space narrowing (K-L grades 1–2) a mean of 8.8 years postoperatively. In Chalmers et al. [126] small cohort of 13 patients, 50% deteriorated by ≥1 K-L grades a mean of 3.3 years after surgery. We reported that 57% of 69 patients had a radiographic progression of joint narrowing a mean of 11.9 years postoperatively. Patients who undergo meniscus transplantation typically have pre-existing articular cartilage deterioration and mild to moderate radiographic OA before surgery and it is therefore not feasible to determine the effect of RTS on progression of joint space narrowing after surgery.

27.5 Conclusions and Comments

The crucial roles of the menisci in the human knee are well understood. The deleterious effects of meniscectomy on tibiofemoral compartment cartilage and long-term clinical outcomes have been reported by multiple studies. Although high RTS rates were noted in a few studies in this chapter, these were offset by deterioration in radiographic OA in 60–90% of patients followed >6 years postoperatively. It is our opinion that in only select cases would meniscectomy be considered over meniscus repair (assuming appropriate indications exist for repair), such as in professional athletes who are willing to risk the development of early knee OA for their athletic career. We have long advocated repair of meniscus tears instead of resection, which we first described in 1987 [78], and then presented in multiple clinical studies [62, 64, 68, 69, 79]. The indications, contraindications, and technical operative details have been discussed in detail elsewhere [51]. We stress the importance of obtaining MRI both preoperatively and postoperatively to determine meniscus healing [62] for repaired radial and complex tears for patient education purposes. Our published systematic review of 23 investigations in which meniscus repairs for tears in the R/W zone were performed [60] demonstrated acceptable healing rates that support repair of meniscus tears under the appropriate indications. In this chapter, >80% of athletes who underwent meniscus repair (either isolated or with ACL reconstruction) were able to RTS. In children and adolescents, every attempt should be made to preserve meniscus tissue and function; otherwise, meniscus transplantation will most likely have to be considered in the third or fourth decade of life. While the majority of patients who undergo meniscus transplantation are able to return to low-impact activities, most authors do not recommend strenuous sports involving extensive twisting, cutting, jumping, or pivoting.

Rehabilitation Criteria for RTS after meniscus procedures were usually not provided. Few other publications are available that describe rehabilitation after meniscus repair or transplantation [143, 144]; we have previously presented our programs in detail for both isolated procedures and combined with ACL reconstruction [92, 145] (see Table 27.7).

References

1. Arno S, Hadley S, Campbell KA, Bell CP, Hall M, Beltran LS, Recht MP, Sherman OH, Walker PS. The effect of arthroscopic partial medial meniscectomy on tibiofemoral stability. Am J Sports Med. 2013;41(1):73–9. https://doi.org/10.1177/0363546512464482.
2. Makris EA, Hadidi P, Athanasiou KA. The knee meniscus: structure-function, pathophysiology, current repair techniques, and prospects for regeneration. Biomaterials. 2011;32(30):7411–31. https://doi.org/10.1016/j.biomaterials.2011.06.037.
3. Mononen ME, Jurvelin JS, Korhonen RK. Effects of radial tears and partial meniscectomy of lateral meniscus on the knee joint mechanics during the stance phase of the gait cycle–a 3D finite element

study. J Orthop Res. 2013;31(8):1208–17. https://doi.org/10.1002/jor.22358.
4. Sturnieks DL, Besier TF, Mills PM, Ackland TR, Maguire KF, Stachowiak GW, Podsiadlo P, Lloyd DG. Knee joint biomechanics following arthroscopic partial meniscectomy. J Orthop Res. 2008;26(8):1075–80. https://doi.org/10.1002/jor.20610.
5. Wang H, Chen T, Torzilli P, Warren R, Maher S. Dynamic contact stress patterns on the tibial plateaus during simulated gait: a novel application of normalized cross correlation. J Biomech. 2014;47(2):568–74. https://doi.org/10.1016/j.jbiomech.2013.11.042.
6. Ahmed AM, Burke DL. In-vitro measurement of static pressure distribution in synovial joints--part I: Tibial surface of the knee. J Biomech Eng. 1983;105(3):216–25.
7. Bourne RB, Finlay JB, Papadopoulos P, Andreae P. The effect of medial meniscectomy on strain distribution in the proximal part of the tibia. J Bone Joint Surg Am. 1984;66(9):1431–7.
8. Pena E, Calvo B, Martinez MA, Palanca D, Doblare M. Finite element analysis of the effect of meniscal tears and meniscectomies on human knee biomechanics. Clin Biomech (Bristol, Avon). 2005;20(5):498–507.
9. Paletta GA, Manning T, Snell E, Parker R, Bergfeld J. The effect of allograft meniscal replacement on intraarticular contact area and pressures in the human knee. A biomechanical study. Am J Sports Med. 1997;25(5):692–8.
10. Fink C, Hoser C, Hackl W, Navarro RA, Benedetto KP. Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture--is sports activity a determining variable? Int J Sports Med. 2001;22(4):304–9.
11. McDermott ID, Amis AA. The consequences of meniscectomy. J Bone Joint Surg Br. 2006;88(12):1549–56. https://doi.org/10.1302/0301-620X.88B12.18140.
12. Meunier A, Odensten M, Good L. Long-term results after primary repair or non-surgical treatment of anterior cruciate ligament rupture: a randomized study with a 15-year follow-up. Scand J Med Sci Sports. 2007;17(3):230–7. https://doi.org/10.1111/j.1600-0838.2006.00547.x.
13. Neuman P, Englund M, Kostogiannis I, Friden T, Roos H, Dahlberg LE. Prevalence of tibiofemoral osteoarthritis 15 years after nonoperative treatment of anterior cruciate ligament injury: a prospective cohort study. Am J Sports Med. 2008;36(9):1717–25. https://doi.org/10.1177/0363546508316770.
14. Petty CA, Lubowitz JH. Does arthroscopic partial meniscectomy result in knee osteoarthritis? A systematic review with a minimum of 8 years' follow-up. Arthroscopy. 2011;27(3):419–24. https://doi.org/10.1016/j.arthro.2010.08.016.
15. Roos EM. Joint injury causes knee osteoarthritis in young adults. Curr Opin Rheumatol. 2005;17(2):195–200.
16. Salata MJ, Gibbs AE, Sekiya JK. A systematic review of clinical outcomes in patients undergoing meniscectomy. Am J Sports Med. 2010;38(9):1907–16. https://doi.org/10.1177/0363546510370196.
17. Thompson WO, Thaete FL, Fu FH, Dye SF. Tibial meniscal dynamics using three-dimensional reconstruction of magnetic resonance images. Am J Sports Med. 1991;19:210–6.
18. Yao J, Lancianese SL, Hovinga KR, Lee J, Lerner AL. Magnetic resonance image analysis of meniscal translation and tibio-menisco-femoral contact in deep knee flexion. J Orthop Res. 2008;26(5):673–84.
19. Mow VC, Ratcliffe A, Chern KY, Kelly MA. Structure and function relationships of the menisci of the knee. In: Mow VC, Arnoczky SP, Jackson DW, editors. Knee meniscus: basic and clinical foundations. New York: Raven Press, Ltd; 1992. p. 37–57.
20. Musahl V, Citak M, O'Loughlin PF, Choi D, Bedi A, Pearle AD. The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. Am J Sports Med. 2010;38(8):1591–7. https://doi.org/10.1177/0363546510364402.
21. Bedi A, Kelly NH, Baad M, Fox AJ, Brophy RH, Warren RF, Maher SA. Dynamic contact mechanics of the medial meniscus as a function of radial tear, repair, and partial meniscectomy. J Bone Joint Surg Am. 2010;92(6):1398–408. https://doi.org/10.2106/JBJS.I.00539.
22. Seedhom BB, Hargreaves DJ. Transmission of the load in the knee joint with special reference to the role of the menisci. Part II. Experimental results, discussion, and conclusions. Eng Med. 1979;8:220–8.
23. Fukubayashi T, Kurosawa H. The contact area and pressure distribution pattern of the knee. A study of normal and osteoarthrotic knee joints. Acta Orthop Scand. 1980;51(6):871–9.
24. Kurosawa H, Fukubayashi T, Nakajima H. Load-bearing mode of the knee joint: physical behavior of the knee joint with or without menisci. Clin Orthop Relat Res. 1980;149:283–90.
25. McDermott ID, Lie DT, Edwards A, Bull AM, Amis AA. The effects of lateral meniscal allograft transplantation techniques on tibio-femoral contact pressures. Knee Surg Sports Traumatol Arthrosc. 2008;16(6):553–60.
26. Seitz AM, Lubomierski A, Friemert B, Ignatius A, Durselen L. Effect of partial meniscectomy at the medial posterior horn on tibiofemoral contact mechanics and meniscal hoop strains in human knees. J Orthop Res. 2012;30(6):934–42. https://doi.org/10.1002/jor.22010.
27. Thieman KM, Pozzi A, Ling HY, Lewis DD, Horodyski M. Contact mechanics of simulated meniscal tears in cadaveric canine stifles. Vet Surg. 2009;38(7):803–10. https://doi.org/10.1111/j.1532-950X.2009.00571.x.
28. Verma NN, Kolb E, Cole BJ, Berkson MB, Garretson R, Farr J, Fregly B. The effects of medial meniscal

transplantation techniques on intra-articular contact pressures. J Knee Surg. 2008;21(1):20–6.
29. Koh JL, Yi SJ, Ren Y, Zimmerman TA, Zhang LQ. Tibiofemoral contact mechanics with horizontal cleavage tear and resection of the medial meniscus in the human knee. J Bone Joint Surg Am. 2016;98(21):1829–36. https://doi.org/10.2106/JBJS.16.00214.
30. Markolf KL, Bargar WL, Shoemaker SC, Amstutz HC. The role of joint load in knee stability. J Bone Joint Surg Am. 1981;63(4):570–85.
31. Kelly BT, Potter HG, Deng XH, Pearle AD, Turner AS, Warren RF, Rodeo SA. Meniscal allograft transplantation in the sheep knee: evaluation of chondroprotective effects. Am J Sports Med. 2006;34(9):1464–77.
32. Szomor ZL, Martin TE, Bonar F, Murrell GA. The protective effects of meniscal transplantation on cartilage. An experimental study in sheep. J Bone Joint Surg Am. 2000;82(1):80–8.
33. Wilson W, van Rietbergen B, van Donkelaar CC, Huiskes R. Pathways of load-induced cartilage damage causing cartilage degeneration in the knee after meniscectomy. J Biomech. 2003;36(6):845–51.
34. McCann L, Ingham E, Jin Z, Fisher J. Influence of the meniscus on friction and degradation of cartilage in the natural knee joint. Osteoarthr Cartil. 2009;17(8):995–1000. https://doi.org/10.1016/j.joca.2009.02.012.
35. Andersson-Molina H, Karlsson H, Rockborn P. Arthroscopic partial and total meniscectomy: A long-term follow-up study with matched controls. Arthroscopy. 2002;18(2):183–9.
36. Cohen SB, Short CP, O'Hagan T, Wu HT, Morrison WB, Zoga AC. The effect of meniscal tears on cartilage loss of the knee: findings on serial MRIs. Phys Sportsmed. 2012;40(3):66–76. https://doi.org/10.3810/psm.2012.09.1983.
37. Han SB, Shetty GM, Lee DH, Chae DJ, Seo SS, Wang KH, Yoo SH, Nha KW. Unfavorable results of partial meniscectomy for complete posterior medial meniscus root tear with early osteoarthritis: a 5- to 8-year follow-up study. Arthroscopy. 2010;26(10):1326–32. https://doi.org/10.1016/j.arthro.2010.01.032.
38. Magnussen RA, Mansour AA, Carey JL, Spindler KP. Meniscus status at anterior cruciate ligament reconstruction associated with radiographic signs of osteoarthritis at 5- to 10-year follow-up: a systematic review. J Knee Surg. 2009;22(4):347–57.
39. Mills PM, Wang Y, Cicuttini FM, Stoffel K, Stachowiak GW, Podsiadlo P, Lloyd DG. Tibiofemoral cartilage defects 3-5 years following arthroscopic partial medial meniscectomy. Osteoarthr Cartil. 2008;16(12):1526–31. https://doi.org/10.1016/j.joca.2008.04.014.
40. Rockborn P, Messner K. Long-term results of meniscus repair and meniscectomy: a 13-year functional and radiographic follow-up study. Knee Surg Sports Traumatol Arthrosc. 2000;8(1):2–10.
41. Roos EM, Ostenberg A, Roos H, Ekdahl C, Lohmander LS. Long-term outcome of meniscectomy: symptoms, function, and performance tests in patients with or without radiographic osteoarthritis compared to matched controls. Osteoarthr Cartil. 2001;9(4):316–24.
42. Scheller G, Sobau C, Bulow JU. Arthroscopic partial lateral meniscectomy in an otherwise normal knee: clinical, functional, and radiographic results of a long-term follow-up study. Arthroscopy. 2001;17(9):946–52. https://doi.org/10.1053/jars.2001.28952.
43. Stein T, Mehling AP, Welsch F, von Eisenhart-Rothe R, Jager A. Long-term outcome after arthroscopic meniscal repair versus arthroscopic partial meniscectomy for traumatic meniscal tears. Am J Sports Med. 2010;38(8):1542–8. https://doi.org/10.1177/0363546510364052.
44. Lyman S, Hidaka C, Valdez AS, Hetsroni I, Pan TJ, Do H, Dunn WR, Marx RG. Risk factors for meniscectomy after meniscal repair. Am J Sports Med. 2013;41(12):2772–8. https://doi.org/10.1177/0363546513503444.
45. Mihelic R, Jurdana H, Jotanovic Z, Madjarevic T, Tudor A. Long-term results of anterior cruciate ligament reconstruction: a comparison with non-operative treatment with a follow-up of 17–20 years. Int Orthop. 2011;35(7):1093–7. https://doi.org/10.1007/s00264-011-1206-x.
46. Nguyen JT, Wasserstein D, Reinke EK, Spindler KP, Mehta N, Doyle JB, Group M, Marx RG. Does the chronicity of anterior cruciate ligament ruptures influence patient-reported outcomes before surgery. Am J Sports Med. 2016; https://doi.org/10.1177/0363546516669344.
47. Sanders TL, Pareek A, Kremers HM, Bryan AJ, Levy BA, Stuart MJ, Dahm DL, Krych AJ. Long-term follow-up of isolated ACL tears treated without ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2016; https://doi.org/10.1007/s00167-016-4172-4.
48. Kennedy J, Jackson MP, O'Kelly P, Moran R. Timing of reconstruction of the anterior cruciate ligament in athletes and the incidence of secondary pathology within the knee. J Bone Joint Surg. 2010;92(3):362–6. https://doi.org/10.1302/0301-620X.92B3.22424.
49. Smith JP 3rd, Barrett GR. Medial and lateral meniscal tear patterns in anterior cruciate ligament-deficient knees. A prospective analysis of 575 tears. Am J Sports Med. 2001;29(4):415–9.
50. Tandogan RN, Taser O, Kayaalp A, Taskiran E, Pinar H, Alparslan B, Alturfan A. Analysis of meniscal and chondral lesions accompanying anterior cruciate ligament tears: relationship with age, time from injury, and level of sport. Knee Surg Sports Traumatol Arthrosc. 2004;12(4):262–70. https://doi.org/10.1007/s00167-003-0398-z.
51. Noyes FR, Barber-Westin SD. Meniscus tears: diagnosis, repair techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors.

Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 677–718. https://doi.org/10.1016/b978-0-323-32903-3.00023-8.
52. Ahn JH, Kim JG, Wang JH, Jung CH, Lim HC. Long-term results of anterior cruciate ligament reconstruction using bone-patellar tendon-bone: an analysis of the factors affecting the development of osteoarthritis. Arthroscopy. 2012;28(8):1114–23. https://doi.org/10.1016/j.arthro.2011.12.019.
53. Barenius B, Ponzer S, Shalabi A, Bujak R, Norlen L, Eriksson K. Increased risk of osteoarthritis after anterior cruciate ligament reconstruction: a 14-year follow-up study of a randomized controlled trial. Am J Sports Med. 2014;42(5):1049–57. https://doi.org/10.1177/0363546514526139.
54. Gerhard P, Bolt R, Duck K, Mayer R, Friederich NF, Hirschmann MT. Long-term results of arthroscopically assisted anatomical single-bundle anterior cruciate ligament reconstruction using patellar tendon autograft: are there any predictors for the development of osteoarthritis? Knee Surg Sports Traumatol Arthrosc. 2013;21(4):957–64. https://doi.org/10.1007/s00167-012-2001-y.
55. Keays SL, Newcombe PA, Bullock-Saxton JE, Bullock MI, Keays AC. Factors involved in the development of osteoarthritis after anterior cruciate ligament surgery. Am J Sports Med. 2010;38(3):455–63. https://doi.org/10.1177/0363546509350914.
56. Li RT, Lorenz S, Xu Y, Harner CD, Fu FH, Irrgang JJ. Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. Am J Sports Med. 2011;39(12):2595–603. https://doi.org/10.1177/0363546511424720.
57. Nakata K, Shino K, Horibe S, Tanaka Y, Toritsuka Y, Nakamura N, Koyanagi M, Yoshikawa H. Arthroscopic anterior cruciate ligament reconstruction using fresh-frozen bone plug-free allogeneic tendons: 10-year follow-up. Arthroscopy. 2008;24(3):285–91.
58. Salmon LJ, Russell VJ, Refshauge K, Kader D, Connolly C, Linklater J, Pinczewski LA. Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. Am J Sports Med. 2006;34(5):721–32.
59. Shelbourne KD, Gray T. Minimum 10-year results after anterior cruciate ligament reconstruction: how the loss of normal knee motion compounds other factors related to the development of osteoarthritis after surgery. Am J Sports Med. 2009;37(3):471–80. https://doi.org/10.1177/0363546508326709.
60. Barber-Westin SD, Noyes FR. Clinical healing rates of meniscus repairs of tears in the central-third (red-white) zone. Arthroscopy. 2014;30(1):134–46. https://doi.org/10.1016/j.arthro.2013.10.003.
61. Kurzweil PR, Lynch NM, Coleman S, Kearney B. Repair of horizontal meniscus tears: a systematic review. Arthroscopy. 2014;30(11):1513–9. https://doi.org/10.1016/j.arthro.2014.05.038.
62. Noyes FR, Chen RC, Barber-Westin SD, Potter HG. Greater than 10-year results of red-white longitudinal meniscal repairs in patients 20 years of age or younger. Am J Sports Med. 2011;39(5):1008–17. https://doi.org/10.1177/0363546510392014.
63. Tagliero AJ, Desai VS, Kennedy NI, Camp CL, Stuart MJ, Levy BA, Dahm DL, Krych AJ. Seventeen-year follow-up after meniscal repair with concomitant anterior cruciate ligament reconstruction in a Pediatric and adolescent population. Am J Sports Med. 2018;46(14):3361–7. https://doi.org/10.1177/0363546518803934.
64. Buseck MS, Noyes FR. Arthroscopic evaluation of meniscal repairs after anterior cruciate ligament reconstruction and immediate motion. Am J Sports Med. 1991;19(5):489–94.
65. Westermann RW, Wright RW, Spindler KP, Huston LJ, Group MK, Wolf BR. Meniscal repair with concurrent anterior cruciate ligament reconstruction: operative success and patient outcomes at 6-year follow-up. Am J Sports Med. 2014;42(9):2184–92. https://doi.org/10.1177/0363546514536022.
66. Choi NH, Kim BY, Hwang Bo BH, Victoroff BN. Suture versus FasT-Fix all-inside meniscus repair at time of anterior cruciate ligament reconstruction. Arthroscopy. 2014;30(10):1280–6. https://doi.org/10.1016/j.arthro.2014.05.023.
67. Feng H, Hong L, Geng XS, Zhang H, Wang XS, Jiang XY. Second-look arthroscopic evaluation of bucket-handle meniscus tear repairs with anterior cruciate ligament reconstruction: 67 consecutive cases. Arthroscopy. 2008;24(12):1358–66.
68. Rubman MH, Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscal tears that extend into the avascular zone. A review of 198 single and complex tears. Am J Sports Med. 1998;26(1):87–95.
69. Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscal tears extending into the avascular zone in patients younger than twenty years of age. Am J Sports Med. 2002;30(4):589–600.
70. Miller MD, Ritchie JR, Gomez BA, Royster RM, DeLee JC. Meniscal repair. An experimental study in the goat. Am J Sports Med. 1995;23(1):124–8.
71. Miller MD, Kline AJ, Jepsen KG. "All-inside" meniscal repair devices: an experimental study in the goat model. Am J Sports Med. 2004;32(4):858–62.
72. Ritchie JR, Miller MD, Bents RT, Smith DK. Meniscal repair in the goat model. The use of healing adjuncts on central tears and the role of magnetic resonance arthrography in repair evaluation. Am J Sports Med. 1998;26(2):278–84.
73. Hospodar SJ, Schmitz MR, Golish SR, Ruder CR, Miller MD. FasT-Fix versus inside-out suture meniscal repair in the goat model. Am J Sports Med. 2009;37(2):330–3. https://doi.org/10.1177/0363546508325667.
74. Allaire R, Muriuki M, Gilbertson L, Harner CD. Biomechanical consequences of a tear of the posterior root of the medial meniscus. Similar to total meniscectomy. J Bone Joint Surg Am.

2008;90(9):1922–31. https://doi.org/10.2106/JBJS.G.00748.
75. Marchetti DC, Phelps BM, Dahl KD, Slette EL, Mikula JD, Dornan GJ, Bucci G, Turnbull TL, Singleton SB. A contact pressure analysis comparing an all-inside and inside-out surgical repair technique for bucket-handle medial meniscus tears. Arthroscopy. 2017;33(10):1840–8. https://doi.org/10.1016/j.arthro.2017.04.013.
76. Masoudi A, Beamer BS, Harlow ER, Manoukian OS, Walley KC, Hertz B, Haeussler C, Olson JJ, Zurakowski D, Nazarian A, Ramappa AJ, DeAngelis JP. Biomechanical evaluation of an all-inside suture-based device for repairing longitudinal meniscal tears. Arthroscopy. 2015;31(3):428–34. https://doi.org/10.1016/j.arthro.2014.08.027.
77. Rosso C, Muller S, Buckland DM, Schwenk T, Zimmermann S, de Wild M, Valderrabano V. All-inside meniscal repair devices compared with their matched inside-out vertical mattress suture repair: introducing 10,000 and 100,000 loading cycles. Am J Sports Med. 2014;42(9):2226–33. https://doi.org/10.1177/0363546514538394.
78. Noyes FR, Mangine RE, Barber S. Early knee motion after open and arthroscopic anterior cruciate ligament reconstruction. Am J Sports Med. 1987;15(2):149–60.
79. Noyes FR, Barber-Westin SD. Arthroscopic repair of meniscus tears extending into the avascular zone with or without anterior cruciate ligament reconstruction in patients 40 years of age and older. Arthroscopy. 2000;16(8):822–9. https://doi.org/10.1053/jars.2000.19434.
80. Steenbrugge F, Van Nieuwenhuyse W, Verdonk R, Verstraete K. Arthroscopic meniscus repair in the ACL-deficient knee. Int Orthop. 2005;29(2):109–12. https://doi.org/10.1007/s00264-004-0616-4.
81. Haklar U, Donmez F, Basaran SH, Canbora MK. Results of arthroscopic repair of partial- or full-thickness longitudinal medial meniscal tears by single or double vertical sutures using the inside-out technique. Am J Sports Med. 2013;41(3):596–602. https://doi.org/10.1177/0363546512472046.
82. Vanderhave KL, Moravek JE, Sekiya JK, Wojtys EM. Meniscus tears in the young athlete: results of arthroscopic repair. J Pediatr Orthop. 2011;31(5):496–500. https://doi.org/10.1097/BPO.0b013e31821ffb8d.
83. O'Shea JJ, Shelbourne KD. Repair of locked bucket-handle meniscal tears in knees with chronic anterior cruciate ligament deficiency. Am J Sports Med. 2003;31(2):216–20.
84. Paxton ES, Stock MV, Brophy RH. Meniscal repair versus partial meniscectomy: a systematic review comparing reoperation rates and clinical outcomes. Arthroscopy. 2011;27(9):1275–88. https://doi.org/10.1016/j.arthro.2011.03.088.
85. Xu C, Zhao J. A meta-analysis comparing meniscal repair with meniscectomy in the treatment of meniscal tears: the more meniscus, the better outcome? Knee Surg Sports Traumatol Arthrosc. 2015;23(1):164–70. https://doi.org/10.1007/s00167-013-2528-6.
86. Ekhtiari S, Khan M, Kirsch JM, Thornley P, Larson CM, Bedi A. Most elite athletes return to competition following operative management of meniscal tears: a systematic review. J ISAKOS Joint Disorders Orthop Sports Med. 2018;3(2):110–5. https://doi.org/10.1136/jisakos-2017-000181.
87. Eberbach H, Zwingmann J, Hohloch L, Bode G, Maier D, Niemeyer P, Sudkamp NP, Feucht MJ. Sport-specific outcomes after isolated meniscal repair: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2018;26(3):762–71. https://doi.org/10.1007/s00167-017-4463-4.
88. Mosich GM, Lieu V, Ebramzadeh E, Beck JJ. Operative treatment of isolated meniscus injuries in adolescent patients: a meta-analysis and review. Sports Health. 2018;10(4):311–6. https://doi.org/10.1177/1941738118768201.
89. Noyes FR, Barber-Westin SD. Meniscus transplantation: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 719–59. https://doi.org/10.1016/b978-0-323-32903-3.00024-x.
90. Getgood A, LaPrade RF, Verdonk P, Gersoff W, Cole B, Spalding T, Group I. International meniscus reconstruction experts forum (IMREF) 2015 consensus statement on the practice of meniscal allograft transplantation. Am J Sports Med. 2016; https://doi.org/10.1177/0363546516660064.
91. Barber-Westin SD, Noyes FR. Low-impact sports activities are feasible after meniscus transplantation: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2018;26(7):1950–8. https://doi.org/10.1007/s00167-017-4658-8.
92. Heckmann TP, Noyes FR, Barber-Westin SD. Rehabilitation of meniscus repair and transplantation procedures. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 760–71. https://doi.org/10.1016/b978-0-323-32903-3.00025-1.
93. Aune KT, Andrews JR, Dugas JR, Cain EL Jr. Return to play after partial lateral meniscectomy in National Football League Athletes. Am J Sports Med. 2014;42(8):1865–72. https://doi.org/10.1177/0363546514535069.
94. Brophy RH, Gill CS, Lyman S, Barnes RP, Rodeo SA, Warren RF. Effect of anterior cruciate ligament reconstruction and meniscectomy on length of career in National Football League athletes: a case control study. Am J Sports Med. 2009;37(11):2102–7. https://doi.org/10.1177/0363546509349035.
95. Mariani PP, Garofalo R, Margheritini F. Chondrolysis after partial lateral meniscectomy in athletes. Knee Surg Sports Traumatol Arthrosc. 2008;16(6):574–80. https://doi.org/10.1007/s00167-008-0508-z.

96. Minhas SV, Kester BS, Larkin KE, Hsu WK. The effect of an orthopaedic surgical procedure in the National Basketball Association. Am J Sports Med. 2016;44(4):1056–61. https://doi.org/10.1177/0363546515623028.
97. Nawabi DH, Cro S, Hamid IP, Williams A. Return to play after lateral meniscectomy compared with medial meniscectomy in elite professional soccer players. Am J Sports Med. 2014;42(9):2193–8. https://doi.org/10.1177/0363546514540271.
98. Sonnery-Cottet B, Archbold P, Thaunat M, Carnesecchi O, Tostes M, Chambat P. Rapid chondrolysis of the knee after partial lateral meniscectomy in professional athletes. Knee. 2014;21(2):504–8. https://doi.org/10.1016/j.knee.2014.01.001.
99. Kim SG, Nagao M, Kamata K, Maeda K, Nozawa M. Return to sport after arthroscopic meniscectomy on stable knees. BMC Sports Sci Med Rehabil. 2013;5(1):23. https://doi.org/10.1186/2052-1847-5-23.
100. Bonneux I, Vandekerckhove B. Arthroscopic partial lateral meniscectomy long-term results in athletes. Acta Orthop Belg. 2002;68(4):356–61.
101. Herrlin SV, Wange PO, Lapidus G, Hallander M, Werner S, Weidenhielm L. Is arthroscopic surgery beneficial in treating non-traumatic, degenerative medial meniscal tears? A five year follow-up. Knee Surg Sports Traumatol Arthrosc. 2013;21(2):358–64. https://doi.org/10.1007/s00167-012-1960-3.
102. Hulet CH, Locker BG, Schiltz D, Texier A, Tallier E, Vielpeau CH. Arthroscopic medial meniscectomy on stable knees. J Bone Joint Surg. 2001;83(1):29–32.
103. Kim JG, Lee SY, Chay S, Lim HC, Bae JH. Arthroscopic meniscectomy for medial meniscus horizontal cleavage tears in patients under age 45. Knee Surg Relat Res. 2016;28(3):225–32. https://doi.org/10.5792/ksrr.2016.28.3.225.
104. Yim JH, Seon JK, Song EK, Choi JI, Kim MC, Lee KB, Seo HY. A comparative study of meniscectomy and nonoperative treatment for degenerative horizontal tears of the medial meniscus. Am J Sports Med. 2013;41(7):1565–70. https://doi.org/10.1177/0363546513488518.
105. Mariani PP, Adriani E, Maresca G. Arthroscopic-assisted posterior cruciate ligament reconstruction using patellar tendon autograft: a technique for graft passage. Arthroscopy. 1996;12(4):510–2.
106. Alvarez-Diaz P, Alentorn-Geli E, Llobet F, Granados N, Steinbacher G, Cugat R. Return to play after all-inside meniscal repair in competitive football players: a minimum 5-year follow-up. Knee Surg Sports Traumatol Arthrosc. 2016;24(6):1997–2001. https://doi.org/10.1007/s00167-014-3285-x.
107. Imade S, Kumahashi N, Kuwata S, Kadowaki M, Ito S, Uchio Y. Clinical outcomes of revision meniscal repair: a case series. Am J Sports Med. 2014;42(2):350–7. https://doi.org/10.1177/0363546513508261.
108. Kraus T, Heidari N, Svehlik M, Schneider F, Sperl M, Linhart W. Outcome of repaired unstable meniscal tears in children and adolescents. Acta Orthop. 2012;83(3):261–6. https://doi.org/10.3109/17453674.2012.693017.
109. Logan M, Watts M, Owen J, Myers P. Meniscal repair in the elite athlete: results of 45 repairs with a minimum 5-year follow-up. Am J Sports Med. 2009;37(6):1131–4.
110. Pujol N, Bohu Y, Boisrenoult P, Macdes A, Beaufils P. Clinical outcomes of open meniscal repair of horizontal meniscal tears in young patients. Knee Surg Sports Traumatol Arthrosc. 2013;21(7):1530–3. https://doi.org/10.1007/s00167-012-2099-y.
111. Schmitt A, Batisse F, Bonnard C. Results with all-inside meniscal suture in pediatrics. Orthop Traumatol Surg Res. 2016;102(2):207–11. https://doi.org/10.1016/j.otsr.2015.12.018.
112. Tucciarone A, Godente L, Fabbrini R, Garro L, Salate Santone F, Chillemi C. Meniscal tear repaired with Fast-Fix sutures: clinical results in stable versus ACL-deficient knees. Arch Orthop Trauma Surg. 2012;132(3):349–56. https://doi.org/10.1007/s00402-011-1391-5.
113. Ahn JH, Kim KI, Wang JH, Kyung BS, Seo MC, Lee SH. Arthroscopic repair of bucket-handle tears of the lateral meniscus. Knee Surg Sports Traumatol Arthrosc. 2015;23(1):205–10. https://doi.org/10.1007/s00167-013-2764-9.
114. Ahn JH, Kwon OJ, Nam TS. Arthroscopic repair of horizontal meniscal cleavage tears with marrow-stimulating technique. Arthroscopy. 2015;31(1):92–8. https://doi.org/10.1016/j.arthro.2014.07.029.
115. Barber FA, Schroeder FA, Barrera Oro F, Beavis RC. FasT-Fix meniscal repair: mid-term results. Arthroscopy. 2008;24(12):1342–8.
116. Chiang CW, Chang CH, Cheng CY, Chen AC, Chan YS, Hsu KY, Chen WJ. Clinical results of all-inside meniscal repair using the FasT-Fix meniscal repair system. Chang Gung Med J. 2011;34(3):298–305.
117. Choi NH, Kim TH, Son KM, Victoroff BN. Meniscal repair for radial tears of the midbody of the lateral meniscus. Am J Sports Med. 2010;38(12):2472–6. https://doi.org/10.1177/0363546510376736.
118. Kotsovolos ES, Hantes ME, Mastrokalos DS, Lorbach O, Paessler HH. Results of all-inside meniscal repair with the FasT-Fix meniscal repair system. Arthroscopy. 2006;22(1):3–9.
119. Krych AJ, Pitts RT, Dajani KA, Stuart MJ, Levy BA, Dahm DL. Surgical repair of meniscal tears with concomitant anterior cruciate ligament reconstruction in patients 18 years and younger. Am J Sports Med. 2010;38(5):976–82. https://doi.org/10.1177/0363546509354055.
120. Lind M, Nielsen T, Fauno P, Lund B, Christiansen SE. Free rehabilitation is safe after isolated meniscus repair: a prospective randomized trial comparing free with restricted rehabilitation regimens. Am J Sports Med. 2013;41(12):2753–8. https://doi.org/10.1177/0363546513505079.
121. Lucas G, Accadbled F, Violas P, Sales de Gauzy J, Knorr J. Isolated meniscal injuries in paediatric

patients: outcomes after arthroscopic repair. Orthop Traumatol Surg Rec. 2015;101(2):173–7. https://doi.org/10.1016/j.otsr.2014.12.006.
122. Majewski M, Stoll R, Widmer H, Muller W, Friederich NF. Midterm and long-term results after arthroscopic suture repair of isolated, longitudinal, vertical meniscal tears in stable knees. Am J Sports Med. 2006;34(7):1072–6.
123. Martin-Fuentes AM, Ojeda-Thies C, Vila-Rico J. Clinical results following meniscal sutures: does concomitant acl repair make a difference? Acta Orthop Belg. 2015;81(4):690–7.
124. Stein T, Mehling AP, Jost K, Auhuber TC, Jager A. Measurements of the quadriceps femoris function after meniscus refixation at the stable athlete's knee. Arch Orthop Trauma Surg. 2009;129(8):1063–9. https://doi.org/10.1007/s00402-009-0852-6.
125. Alentorn-Geli E, Vazquez RS, Diaz PA, Cusco X, Cugat R. Arthroscopic meniscal transplants in soccer players: outcomes at 2- to 5-year follow-up. Clin J Sport Med. 2010;20(5):340–3. https://doi.org/10.1097/JSM.0b013e3181f207dc.
126. Chalmers PN, Karas V, Sherman SL, Cole BJ. Return to high-level sport after meniscal allograft transplantation. Arthroscopy. 2013;29(3):539–44. https://doi.org/10.1016/j.arthro.2012.10.027.
127. Noyes FR, Barber-Westin SD, Rankin M. Meniscal transplantation in symptomatic patients less than fifty years old. J Bone Joint Surg Am. 2004;86-A(7):1392–404.
128. Marcacci M, Marcheggiani Muccioli GM, Grassi A, Ricci M, Tsapralis K, Nanni G, Bonanzinga T, Zaffagnini S. Arthroscopic meniscus allograft transplantation in male professional soccer players: a 36-month follow-up study. Am J Sports Med. 2014;42(2):382–8. https://doi.org/10.1177/0363546513508763.
129. Noyes FR, Barber-Westin SD. Long-term survivorship and function of meniscus transplantation. Am J Sports Med. 2016;44(9):2330–8. https://doi.org/10.1177/0363546516646375.
130. Zaffagnini S, Grassi A, Marcheggiani Muccioli GM, Benzi A, Roberti di Sarsina T, Signorelli C, Raggi F, Marcacci M. Is sport activity possible after arthroscopic meniscal allograft transplantation? Midterm results in active patients. Am J Sports Med. 2016; https://doi.org/10.1177/0363546515621763.
131. Stone KR, Pelsis JR, Surrette ST, Walgenbach AW, Turek TJ. Meniscus transplantation in an active population with moderate to severe cartilage damage. Knee Surg Sports Traumatol Arthrosc. 2015;23(1):251–7. https://doi.org/10.1007/s00167-014-3246-4.
132. Abat F, Gelber PE, Erquicia JI, Tey M, Gonzalez-Lucena G, Monllau JC. Prospective comparative study between two different fixation techniques in meniscal allograft transplantation. Knee Surg Sports Traumatol Arthrosc. 2013;21(7):1516–22. https://doi.org/10.1007/s00167-012-2032-4.
133. Gonzalez-Lucena G, Gelber PE, Pelfort X, Tey M, Monllau JC. Meniscal allograft transplantation without bone blocks: a 5- to 8-year follow-up of 33 patients. Arthroscopy. 2010;26(12):1633–40. https://doi.org/10.1016/j.arthro.2010.05.005.
134. Kempshall PJ, Parkinson B, Thomas M, Robb C, Standell H, Getgood A, Spalding T. Outcome of meniscal allograft transplantation related to articular cartilage status: advanced chondral damage should not be a contraindication. Knee Surg Sports Traumatol Arthrosc. 2015;23(1):280–9. https://doi.org/10.1007/s00167-014-3431-5.
135. Lee BS, Bin SI, Kim JM. Articular cartilage degenerates after subtotal/Total lateral meniscectomy but radiographic arthrosis progression is reduced after meniscal transplantation. Am J Sports Med. 2016;44(1):159–65. https://doi.org/10.1177/0363546515612076.
136. Mahmoud A, Young J, Bullock-Saxton J, Myers P. Meniscal allograft transplantation: the effect of cartilage status on survivorship and clinical outcome. Arthroscopy. 2018;34(6):1871–1876.e1871. https://doi.org/10.1016/j.arthro.2018.01.010.
137. Marcacci M, Zaffagnini S, Marcheggiani Muccioli GM, Grassi A, Bonanzinga T, Nitri M, Bondi A, Molinari M, Rimondi E. Meniscal allograft transplantation without bone plugs: a 3-year minimum follow-up study. Am J Sports Med. 2012;40(2):395–403. https://doi.org/10.1177/0363546511424688.
138. Stone KR, Adelson WS, Pelsis JR, Walgenbach AW, Turek TJ. Long-term survival of concurrent meniscus allograft transplantation and repair of the articular cartilage: a prospective two- to 12-year follow-up report. J Bone Joint Surg. 2010;92(7):941–8. https://doi.org/10.1302/0301-620X.92B7.23182.
139. Vundelinckx B, Bellemans J, Vanlauwe J. Arthroscopically assisted meniscal allograft transplantation in the knee: a medium-term subjective, clinical, and radiographical outcome evaluation. Am J Sports Med. 2010;38(11):2240–7. https://doi.org/10.1177/0363546510375399.
140. Yoon KH, Lee SH, Park SY, Kim HJ, Chung KY. Meniscus allograft transplantation: a comparison of medial and lateral procedures. Am J Sports Med. 2014;42(1):200–7. https://doi.org/10.1177/0363546513509057.
141. Yoon KH, Lee SH, Park SY, Jung GY, Chung KY. Meniscus allograft transplantation for discoid lateral meniscus: clinical comparison between discoid lateral meniscus and nondiscoid lateral meniscus. Arthroscopy. 2014;30(6):724–30. https://doi.org/10.1016/j.arthro.2014.02.017.
142. Zaffagnini S, Grassi A, Marcheggiani Muccioli GM, Benzi A, Serra M, Rotini M, Bragonzoni L, Marcacci M. Survivorship and clinical outcomes of 147 consecutive isolated or combined arthroscopic bone plug free meniscal allograft transplantation. Knee Surg Sports Traumatol Arthrosc. 2016; https://doi.org/10.1007/s00167-016-4035-z.

143. O'Donnell K, Freedman KB, Tjoumakaris FP. Rehabilitation protocols after isolated meniscal repair: a systematic review. Am J Sports Med. 2017;45(7):1687–97. https://doi.org/10.1177/0363546516667578.
144. Cavanaugh JT, Killian SE. Rehabilitation following meniscal repair. Curr Rev Musculoskelet Med. 2012;5(1):46–58. https://doi.org/10.1007/s12178-011-9110-y.
145. Noyes FR, Heckmann TP, Barber-Westin SD. Meniscus repair and transplantation: a comprehensive update. J Orthop Sports Phys Ther. 2012;42(3):274–90. https://doi.org/10.2519/jospt.2012.3588.

28 Return to Sport After Patellofemoral Realignment and Stabilization Procedures

Frank R. Noyes and Sue Barber-Westin

28.1 Introduction

Injuries and disorders of the patellofemoral joint are some of the most common causes of knee pain and frequently include inflammation of the parapatellar soft tissues, damage to the articular cartilage of the patella and/or femoral sulcus, and instability (subluxation or dislocation) [1]. The terminology used to describe patellofemoral disorders can be confusing. *Patellar malalignment* is a translational or rotational deviation of the patella relative to any axis caused by an abnormal relationship between the patella, the soft tissues surrounding the patella, and the femoral and tibial osseous structures. The abnormalities may be caused by congenital issues, such as peripatellar tissue tightness or laxity, a shallow or convex trochlear groove, bony abnormalities of the patella, rotational malalignment of the femur and tibia, patella alta, or patella baja, and may be exacerbated by inflexibility or weakness of the lower extremity musculature. Patellar malalignment may also arise from an injury that disrupts soft tissue stabilizers, especially the medial tissues restraints, including the medial patellofemoral ligament (MPFL). Patellar dislocations and patellofemoral instability are common problems in young athletic individuals. In a study that analyzed factors associated with patellar dislocations in 40,544 injured knees in the United States, Waterman et al. [2] reported that 52% of the injuries occurred during athletics. The peak incidence of dislocations occurred between 15 and 19 years of age. Redislocation rates of first-time patella dislocations treated conservatively range from 36% to 71% in pediatric populations [3, 4] and from 14% to 57% in adult populations [5, 6].

While many patients who sustain patellar dislocations may be successfully treated with conservative measures, surgery is required to prevent recurrent dislocations and the subsequent patellofemoral cartilage damage that occurs. Patients with distinct anatomical abnormalities described in detail elsewhere are more likely to undergo repetitive dislocations unless there is surgical intervention. Many surgical procedures have been described for realignment or stabilization of the patellofemoral mechanism including proximal realignment, distal realignment, or a combination of both (Fig. 28.1). Proximal realignment procedures alter the medial-lateral position of the patella through balancing of soft tissue restraints proximal to its inferior pole and include MPFL repair or reconstruction (Fig. 28.2), medial retinacular capsular and medial patellomeniscal plication, vastus medialis obliquus advancement, and lateral retinacular release. Distal realignment

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_28

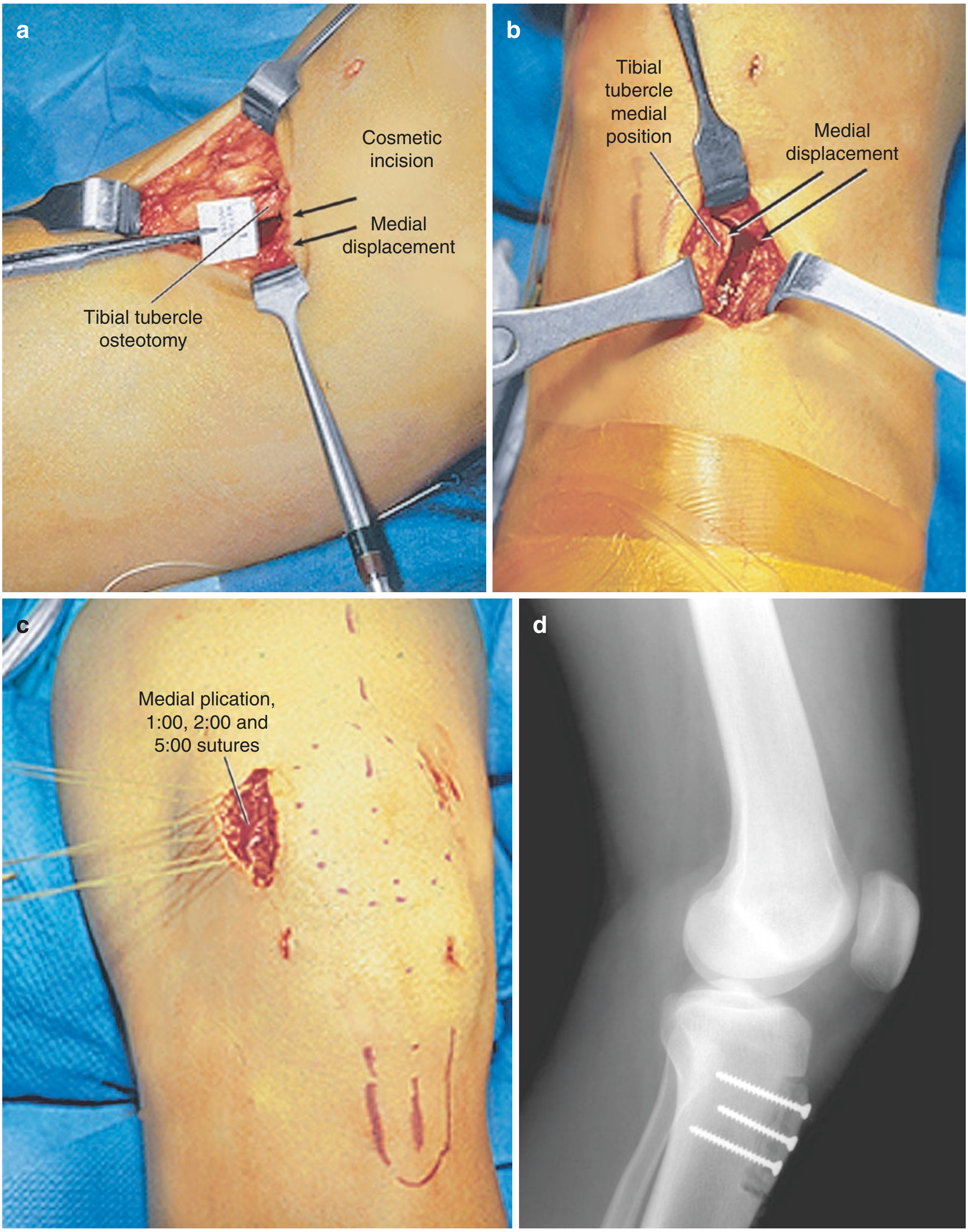


Fig. 28.1 Proximal-distal realignment procedure. (**a**) The medial retinaculum and vastus medialis obliquus 2 cm above the patella are advanced in line of their insertions to restore patellar stability. (**b**) The millimeters of tibial tubercle medial displacement requires are measured at surgery. (**c**) A dovetail tibial tubercle osteotomy has been performed, maintaining the distal and medial soft tissues. (**d**) Postoperative radiograph (From Noyes and Barber-Westin [1])

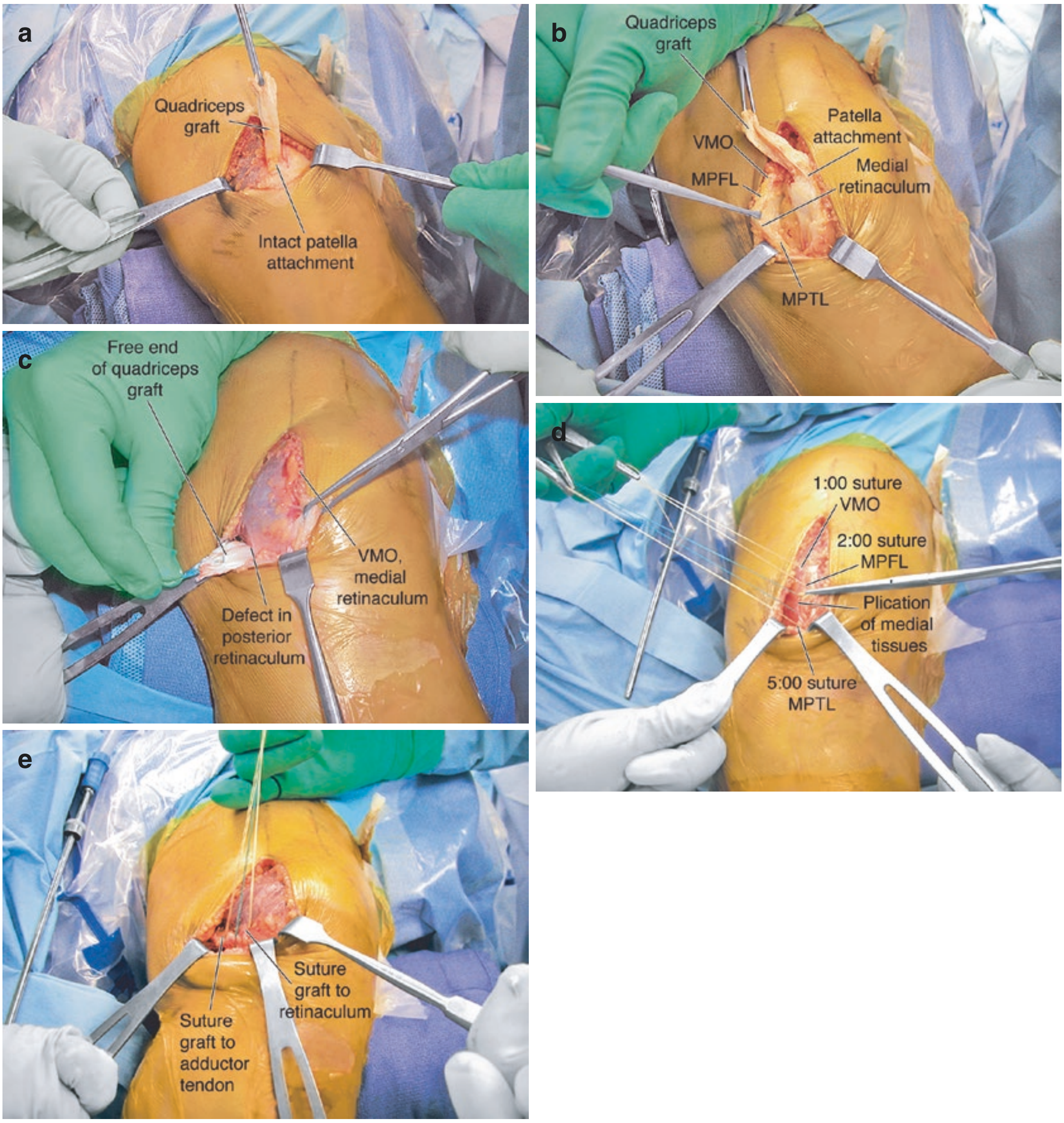


Fig. 28.2 Medial patellofemoral ligament (MPFL) reconstruction with quadriceps tendon. (**a**) A medial full-thickness quadriceps tendon graft, 60 mm × 8 mm wide (measured to the superior edge of the patella) is harvested with the patellar attachment retained. In some knees, a partial-thickness autograft provides a suitably sized graft. Two to 3 mm of the remaining quadriceps tendon is left attached to the vastus medialis obliquus (VMO) for later closure. (**b**) Dissection deep to the medial retinaculum and above synovial pouch and MPFL, medial patello-meniscal ligament (MPML). (**c**) Puncture of the medial retinaculum, posterior to the medial femoral epicondyle at the native MPFL attachment just anterior to the adductor tendon, with the passage of graft beneath the retinaculum. Setting of the normal tension of the medial soft tissues. (**d**) Imbrication of the VMO, medial retinaculum, MPFL, and MPML. (**e**) Suturing of the quadriceps graft to the MPFL native femoral attachment, with a backup suture to the adductor tendon. The graft and medial tissues are not overtensioned and should allow a normal lateral translation (glide) of 25% patellar width (From Noyes and Barber-Westin [1])

procedures modify the medial-lateral, anterior-posterior, rotations, and proximal-distal positions of the patella by transfer of the tibial tubercle. Included in this category are anterior (Maquet [7]), medial (Elmslie-Trillat [8]), and anteromedial (Fulkerson [9]) transfer of the tibial tubercle. Literally, hundreds of articles have been written on these operative procedures regarding their indications, technique, and clinical outcomes [4, 10–20]. However, information regarding the ability of patients to return to sports (RTS) and previous activity levels after these operations is more difficult to determine and, as of the time of writing, no formal systematic review had been conducted on this topic.

Few detailed postoperative rehabilitation guidelines specific for RTS after patellofemoral realignment operations are available. In 2018, Zaman et al. [21] reviewed 53 studies to determine criteria for RTS after MPFL reconstruction. The authors reported that although 35 studies (66%) provided an expected timeline for RTS, only eight included objective criteria in the rehabilitation protocol, such as sufficient quadriceps or general muscle strength, range of motion (ROM), and patellar stability. However, none of the eight studies provided numerical values for these criteria. Fisher et al. [18] reviewed the literature to determine the ability of an MPFL reconstruction to return patients to sports activities. Of 21 studies included in the investigation, only six provided sports activity level ratings (Tegner scores) and the authors concluded that there was very limited RTS information available.

Menetrey et al. [22] reviewed the literature to devise a RTS protocol after patellar dislocation or surgery for patellofemoral instability. These authors also concluded that available evidence regarding the functional capacity of patients, including rehabilitation and testing protocols, that allowed for a safe RTS was sparse. They provided the following criteria from a consensus meeting from the ISAKOS Sports Medicine Committee held in 2013 on RTS after patellofemoral instability: (1) postoperative complete radiographic healing of bone, (2) no knee pain, effusion, or instability, (3) full or nearly full ROM, (4) completion of neuromuscular training and proprioception, (5) satisfactory core strength and endurance, (6) acceptable dynamic control (Star Excursion Balance Test, SEBT), (7) limb symmetry index >85% on hop tests, (8) adequate performance with physiotherapist during sport-specific drills simulating the intensity and movement patterns of the athlete's sport, and (9) psychological readiness to RTS (Single Assessment Numerical Evaluation [SANE] score > 80/100). The authors recommended consideration of several videotaped tests to determine dynamic control, including the single-leg squat, the drop-jump, the side-hop, and the SEBT.

We have published elsewhere a complete description of the management of active patients with patellofemoral malalignment and instability, including a review of the biomechanics of patellofemoral restraints, indications, and contraindications for surgery, and postoperative management [1]. This chapter summarizes data from 52 studies regarding RTS after MPFL reconstruction and proximal/distal realignment procedures that did not involve MPFL reconstruction (Table 28.1). Data regarding return to

Table 28.1 Summary of studies reviewed

	All studies reviewed		RTS incidence rate		Tegner scores only	
	No. of studies	No. of patients	No. of studies	No. of patients	No. of studies	No. of patients
MPFL reconstruction	36	1408	16	677	20	731
Patellar realignment procedures	16	484	5	173	11	311
Total	52	1892	21	850	31	1042

All data are numbers
MPFL medial patellofemoral ligament, *RTS* return to sports

preinjury sport and return to any type of sport, as well as Tegner activity scores and failure rates are provided. An analysis of the postoperative rehabilitation criteria for RTS described by each study is presented. Our postoperative rehabilitation protocol is detailed, along with our criteria to initiate sports training and for final RTS release.

28.2 Return to Sport After MPFL Reconstruction

Our review located 36 studies that provided RTS percentages (Table 28.2) and/or Tegner activity scores (Table 28.3) after MPFL reconstruction in 1408 patients [23–58]. The mean age was approximately 22.8 years (range, 10.3–56) and the gender breakdown, provided in 31 studies, was 717 females and 481 males. The mean follow-up was 3.2 years (range, 0.3–13 years).

The MPFL was reconstructed in all patients in 30 studies and hamstring tendon autografts were used in the majority (23 studies). MPFL reconstruction or repair was selected based on indications in one investigation [38] or in a randomized trial design in two studies [46, 52]. MPFL suture repair was used in acute ruptures in two studies [26, 28] and for chronic recurrent dislocations in one [29]. Associated procedures were described in 12 studies, with the most common including tibial tuberosity transfer, lateral release, and trochleoplasty.

Return to preinjury sports activity levels, provided in 14 studies encompassing 387 patients, averaged 70% (range, 22–100%, Fig. 28.3). Data regarding return to any sport, found in 15 studies, averaged 83% (range, 43–100%). The mean postoperative Tegner score, calculated from 29 studies (Fig. 28.4), was 5.2 points.

The mean time patients were usually allowed to RTS was found in 21 studies (Table 28.4). Almost no criteria were provided to determine when patients could be released safely to either sports-specific training or unrestricted activities. Carnesecchi et al. [23] allowed RTS “depending on the analytical and functional recovery” of the patient. Drez et al. [25] allowed RTS when full ROM and normal quadriceps strength had been achieved. Tompkins et al. [38] released patients to full sports once they passed a “functional assessment”; however, no information regarding tests used or passing criteria was provided.

Ambrozic et al. [35] described sports activity levels in 29 patients (14 females, 15 males, mean age, 26.2 years) who underwent isolated MPFL gracilis autograft reconstruction for recurrent dislocation. RTS was permitted 6 months postoperatively. Twenty-six patients were active in sports before surgery and three never participated. An average of 6.4 years postoperatively, 23 patients had RTS, with 16 obtaining their preinjury level. The most common sports patients returned to were soccer, cycling, and skiing. There were no complications or failures.

Lippacher et al. [28] also focused on the ability of a MPFL reconstruction to return patients to sports activities. These authors followed 68 patients (44 females, 24 males, mean age, 18.3 years) a mean of 2 years postoperatively. Sixty-two patients participated in sports before surgery and all were able to return; 53% at the same or higher level and 47% at lower levels. Common sports patients returned to included soccer, volleyball/handball, cycling, and swimming. Recurrent dislocations occurred in two patients and five patients had 1–2 episodes of subluxation. All of these individuals underwent further rehabilitation and none required revision surgery.

28.3 Return to Sport After Patellar Realignment Procedures

We found 16 studies that provided RTS data after patellar realignment procedures (that did not include MPFL repair or reconstruction) in 484 patients [39, 58–72]. The mean age was approximately 22.2 (range, 5–56) and the gender numbers, provided in 13 studies, were 264 females and 116 males. The mean follow-up was approximately 7 years (range, 0.5–46 years). The operative procedures included Elmslie-Trillat in four

Table 28.2 RTS after MPFL reconstruction

Study	Cohort			MPFL graft, associated procedures[a]	Sports scale	RTS data				% Failed
	No. of men, women	Mean age (range)	Mean follow-up year			RTS % preinjury	RTS % any sport	Mean time RTS allowed (months)	Comments	
Carnesecchi et al. [23]	14/16	21.9 (NP)	1	Gracilis	None	100%	100%	4	RTS allowed "depending on the analytical and functional recovery"	0%
Nelitz et al. [24]	15/6	12.1 (10.3–13.9)	2.8	Gracilis. All open growth plates	Tegner	81%	100%	3	Tegner preop 6.0, FU 5.8; mean time RTS 5.3 months (4–12); 19% returned lower level	0%
Drez et al. [25]	10/5	22 (14–52)	2.6	Semitendinosus or gracilis	Tegner	80%	100%	6	Tegner preop 6.8, FU 6.7. Full activity allowed full ROM and normal quadriceps strength achieved	7%
Nelitz et al. [26]	14, 9	19.2 (15.4–23.6)	2.5	Gracilis and trochleoplasty	Tegner	74%	100%	3	Tegner preop 5.5, FU 5.0. Patients advised to avoid high-risk pivoting activities	0%
Panni et al. [27]	11/37	28 (16–50)	2.7	Semitendinosus	None	64%	100%	6	20% returned to lower level sports for knee-related reasons, 16% returned to lower level for non-knee-related reasons. Gentle jogging on trampoline begun at 8 weeks, controlled sports-specific rehabilitation begun at 12 weeks	0%
Lippacher et al. [28]	24/44	18.3 (14–43)	2	Gracilis	Tegner	53%	91%	3	Tegner preop 4.5, FU 4.0. 47% returned lower level. Common sports: soccer, volleyball, handball, cycling, swimming, skiing. Patients advised of risks of high-pivot sports	0%

Camp et al. [29]	14/13	19 (11–32)	4	MPFL repair (chronic), microfracture 21%, lateral release 3%	Tegner	88%	88%	NP	Tegner preop 6.9, FU 6.6	28%
Ahmad et al. [30]	4/4	32 (16–56)	3	MPFL repair (acute)	None	86%	86%	4	None	12.5%
Ronga et al. [31]	21/7	32.5 (19–40)	3.1	Gracilis	Authors' own	32%	86%	Sports-specific rehab 3, full sports 6	54% returned lower level; mean time RTS 7.5 months (6–16); isokinetic testing 60° and 120°/s involved side significantly weaker than noninvolved	3.5%
Mariani et al. [32]	11/6	21 (14–42)	2.2	MPFL repair (acute)	None	82%	82%	NP	None	0%
Feller et al. [33]	15/21	NP (14–44)	3.1	Semitendinosus or gracilis; transfer tibial tuberosity 25%	Authors' own	NP	81% isolated MPFL, 70% combined	NP	Highest level of sports activities: isolated MPFL 81% strenuous, 19% moderate. Combined 57% strenuous, 20% moderate, 14% light. Frequency of sport: isolated MPFL 47% 4–7 day/week, 43% 1–3 day/week, 5% 1–3 ×/month Combined 43% 4–7 day/week, 57% 1–2 day/week	0%
Wagner et al. [34]	17/33	19 (NP)	1–2	Gracilis	Tegner	80%	80%	NP	Tegner scores NP	6%
Ambrozic and Novak [35]	15/14	26.2 (17–40)	6.4	Gracilis	Tegner	70%	79%	6	Tegner preop 4.4, FU 5.7. Cycling and jogging allowed after 3 months. Common sports soccer, cycling, skiing	3%
Howells et al. [36]	84/109	26 (16–49)	1.3	Semitendinosus	Tegner	NP	76%	NP	Tegner preop NP, FU 5.3. 13% sports with symptoms	0%

(continued)

Table 28.2 (continued)

Study	Cohort			MPFL graft, associated procedures[a]	Sports scale	RTS data				% Failed
	No. of men, women	Mean age (range)	Mean follow-up year			RTS % preinjury	RTS % any sport	Mean time RTS allowed (months)	Comments	
Hopper et al. [37]	Total 61	23.9 (14–46)	2.6	Semitendinosus or gracilis; transfer tibial tuberosity 31%	Tegner	NP	56% (54) mild trochlear dysplasia; 43% (7) severe trochlear dysplasia	NP	Tegner preop NP, FU mild trochlear dysplasia 3.9, severe trochlear dysplasia 2.3	9% mild trochlear dysplasia; 100% severe trochlear dysplasia
Tompkins et al. [38]	7/16	20 (NP)	2–6.2	MPFL repair (14) or hamstring reconstruction (9)	Tegner	64% repair, 22% reconstruction	NP	5–6	Tegner preop repair 5.5, reconstruction 8; FU repair 6.5, reconstruction 5. Patients allowed to RTS once they passed a functional assessment	0%

FU follow-up, *MPFL* medial patellofemoral ligament, *NP* not provided, *ROM* range of motion, *RTS* return to sport

[a]All autografts

Table 28.3 Studies reporting Tegner scores only after MPFL reconstruction

Study	Cohort			MPFL graft, associated procedures[a]	RTS data			% Failed
	No. of men, women	Mean age (range)	Mean follow-up year		Mean time RTS allowed (months)	Tegner preop[b]	Tegner FU[b]	
Lim et al. [39]	6/3	20.2 (14–23)	1	Gracilis	NP	5	6.8	0%
Xie et al. [40]	Total 85	NP	5	Semitendinosus; suture augmentation 49%, transfer tibial tubercle 87%	4	3.3 ± 1.7 augmentation, 3.5 ± 1.8 no augmentation	6.8 ± 1.3 augmentation, 5.5 ± 1.9 no augmentation	2.4% augmentation, 23% no augmentation
Blond and Haugegaard [41]	Total 29	19 (12–39)	2.4	Gracilis and trochleoplasty	NP	4 (1–6)	6 (4–9)	17%
Banke et al. [42]	6/11	22.2 (NP)	2.5	Gracilis and trochleoplasty	NP	2 (0–4)	6 (3–8)	0%
Li et al. [43]	28/37	29.4 (NP)	6.5	Allograft	6	3.1 ± 0.6	5.8 ± 0.9	0%
Berruto et al. [44]	9/7	19 (15–43)	3.3	Synthetic ligament	6	3.9 (3–5)	5.7 (3–7)	0%
Calanna et al. [45]	12/7	25.5 (NP)	1.8	Semitendinosus	5–6	6.1 ± 1.1	5.7 ± 0.8	0%
Zhao et al. [46]	15/73	24 (16–43)	5	Semitendinosus or medial retinaculum repair + lateral release; transfer tibial tubercle 89%	4	3.1 ± 1.9 reconstruction, 2.9 ± 1.6 repair	5.7 ± 1.7 reconstruction, 4.0 ± 1.4 repair	9% reconstruction, 26% repair
Ahmad et al. [47]	Total 20	23 (11–43)	2.6	Semitendinosus autograft or allograft. Lateral release 60%	Running and agility training 3, full sports 4	3.6	5.6	0%
Csintalan et al. [48]	12/37	24 (13–49)	4.3	Semitendinosus	NP	6.1 ± 2.7	5.6 ± 2.5	0%
Becher et al. [49]	10/20	22 (NP)	2.2	Gacilis	NP	NP	Dynamic technique 5.2 ± 1.9, static technique 4.4 ± 1.8	3%
Steiner et al. [50]	12/22	27 (NP)	5.5	Variety graft options	NP	3.1 ± 1.6	5.1 ± 1.6	0%
Hinterwimmer et al. [51]	6/13	23 (16–47)	1.3	Gracilis	NP	NP	5 (3–7)	0%

(continued)

Table 28.3 (continued)

Study	Cohort: No. of men, women	Cohort: Mean age (range)	Cohort: Mean follow-up year	MPFL graft, associated procedures[a]	RTS data: Mean time RTS allowed (months)	RTS data: Tegner preop[b]	RTS data: Tegner FU[b]	% Failed
Ma et al. [52]	22/41	28 (NP)	3.3	Semitendinosus or medial retinaculum plasty and lateral release	3	3 (1–5)	5 (2–8)	0%
Song et al. [53]	10/10	21 (13–34)	2.8	Semitendinosus	3–6	3 (1–4)	5 (4–7)	0%
Kohn et al. [54]	14/28	22 (13–46)	2	Revision gracilis; variety associated procedures in 64%	NP	2.4 (0–7)	4.9 (3–8)	0%
Suganuma et al. [55]	16/30	20 (14–34)	4	Synthetic ligament	3	4.6 (3–7)	4.6 (3–7)	0%
Matthews et al. [56]	12/9	24 (17–44)	2.6	Semitendinosus or gracilis	3–6	3 (0–6)	4.4 (1–7)	0%
Christiansen et al. [57]	15/29	22 (12–47)	1.8	Gracilis; transfer tibial tuberosity 27%	Controlled sports 3, contact sports 6	NP	4 (1–9)	2%
Sillanpaa et al. [58]	Total 15	20.2 (19–22)	10.1	Adductor magnus tenodesis	NP	NP	4 (2–8)	7%

FU follow-up, *MPFL* medial patellofemoral ligament, *NP* not provided, *RTS* return to sport
[a]Autografts unless otherwise indicated
[b]All data given as provided in study

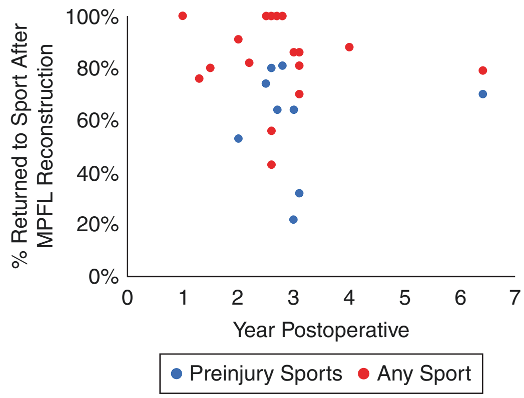


Fig. 28.3 Percentages of athletes who returned to either preinjury sports activities and/or any sport after MPFL reconstruction. A mean of 70% returned to preinjury activity levels and a mean of 83% returned to any sport

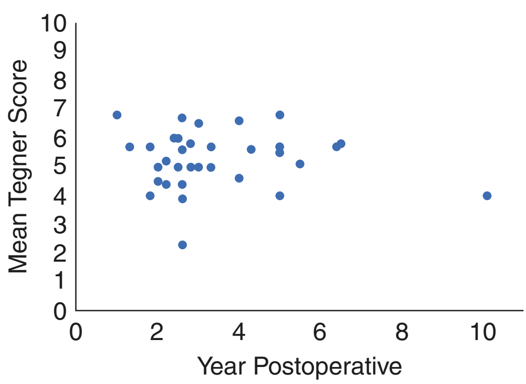


Fig. 28.4 Mean Tegner scores at follow-up after MPFL reconstruction in 29 studies

studies, Elmslie-Trillat-Roux in two studies, Fulkerson in two studies, Roux-Goldthwait in one study, Grammont in one study, and a variety of procedures offered in six studies. Associated procedures were described in nine studies and most frequently included lateral release. Trochleoplasty was done in two studies in select patients.

Return to preinjury sports activity levels was provided in only five studies involving 173 patients (Table 28.5). Percentages ranged from 22% to 97%. Postoperative Tegner activity scores were found in 13 studies (Table 28.6) and averaged 4.1 points (Fig. 28.5).

The mean time patients were usually allowed to RTS was provided in seven studies (Table 28.4). Criteria for RTS was sparse. Tjoumakaris et al. [71] required "adequate" quadriceps strength and ROM. Luhmann et al. [67], in a study involving 27 children (aged 8.8–18.3 years), cited adequate radiographic healing, knee ROM, and near normal leg strength as criteria. Barber and McGarry [59] had similar requirements for RTS.

Liu et al. [66] specifically analyzed RTS after a Fulkerson tibial tubercle anteromedialization for a primary diagnosis of patellofemoral pain or osteoarthritis. A total of 57 patients (48 females, 9 males, mean age, 29.6 years) were followed a mean of 4.6 years postoperatively. Patients were typically allowed to RTS between 6 and 8 months but had to demonstrate "quality movement strate-

Table 28.4 Mean times postoperative sports participation allowed

Operation	Months RTS postoperatively	Qualifications	Number of studies
MPFL reconstruction or repair	3	Running, agility training only	1
	3	Controlled sports only	1
	3	None	5
	4	None	5
	6	None	7
	3–6	None	2
	5–6	None	2
Proximal and/or distal realignment, no MPFL reconstruction or repair	2–3	None	1
	3	None	1
	4–5	None	3
	6	None	1
	6-8	Except contact sports with cutting/pivoting	1
	9	Contact sports with cutting, pivoting	1

Table 28.5 RTS after patellar realignment procedures

Study	Cohort			Operative details, associated procedures	Sports scale (preinjury sports)	RTS data				% Failed
	No. of men, women	Mean age (range)	Mean follow-up year			RTS % preinjury	RTS % any sport	Mean time RTS allowed (months)	Comments	
Tjoumakaris et al. [71]	4/30	20 (14–54)	3.8	Fulkerson and lateral release	None	97%	97%	4–5 "adequate" quadriceps strength and ROM	All athletes; 14 high school, 12 collegiate, 8 recreational	3%
Liu et al. [66]	9/48	29.6 (NP)	4.6	Fulkerson; lateral release 68%	Authors' own	54%	70%	6–8; contact sports with cutting/ pivoting 9 months	RTS "must have shown quality movement strategies on a sport-specific RTS assessment". Most common: walking for exercise, running, cycling, weight lifting, soccer, yoga. 58% considered knee to feel normal during sports	0%
Kreuz et al. [65]	11/17	15 (5–28)	6.3	Proximal realignment, proximal-distal realignment, or proximal realignment-transfer tibial tubercle	None	36%	64%	NP	Redislocation rates: 4 (31%) proximal realignment, 2 (29%) distal realignment, 1 (12.5%) proximal realignment-transfer tibial tubercle	31% redislocation; 18% reoperation
Berruto et al. [60]	12/28	25.8 (16–44)	12.7	Elmslie-Trillat, insall, or open lateral release	Tegner	22%	NP	NP	Tegner FU 4.0 ± 1.7	<1%
Sillanpaa et al. [70]	16/1	20 (19–22)	7	Medial reefing 78%, Roux-Elmslie 22%	Tegner	76%	NP	NP	Tegner FU 5 (2–9)	0%

NP not provided, *ROM* range of motion, *RTS* return to sports

Table 28.6 Studies reporting Tegner scores only after patellar realignment procedures

Study	Cohort			Operative details, associated procedures	RTS data			% Failed
	No. of men, women	Mean age (range)	Mean follow-up year		Mean time RTS allowed (months)	Tegner preop[a]	Tegner FU[a]	
Luhmann et al. [67]	5/22	14.1 (8.8–18.3)	5	Proximal realignment, lateral release; distal realignment 78%	Light jogging 3, full sports 4.5 (adequate radiographic healing, knee ROM, near normal leg strength)	NP	5.4 (1–9)	7%
Marcacci et al. [68]	7/8	21.1 (13–37)	5	Elmslie-Trillat; trochleoplasty 22%	2–3	2 (0–3)	5 (3–7)	0%
Kraus et al. [64]	10/33	14.6 (12.7–16)	8	Grammont realignment; osteochondral fragment fixation 23%	3	6.2 (2–10)	5 (2–9)	7%
Sillanpaa et al. [58]	Total 21	20 (19–24)	7	Roux-Goldthwait	NP	NP	5 (2–7)	14%
Endres and Wilke [62]	4/14	28.2 (17–48)	9.7	Roux-Elmslie-Trillat, lateral release	NP	3.4	4.6	5%
Carney et al. [61]	12/2	NP (17–24)	2.2	Roux-Elmslie-Trillat	NP	NP	4 (1–8); 60% ≤level 3, 33% level 5–6, 7% level 8	7%
Rillmann et al. [69]	Total 32	23.2 (15–42)	5.2	Elmslie-Trillat	NP	3.1 ± 1.2	3.8 ± 0.9	8%
Barber and McGarry [59]	9/26	27.7 (13–52)	8.2	Elmslie-Trillat, lateral release	Running 3, full sports 4–5 (with radiographic healing, full ROM, good quadriceps strength)	NP	3.8	3%
Karataglis et al. [63]	8/30	31 (19–56)	3.3	Elmslie-Trillat; medial plication 18%	NP	NP	3.5 (2–8)	5%
Lim et al. [39]	9/5	21.3 (14–32)	1.3	Distal realignment	NP	1.4	3.4	0%
Vivod et al. [72]	Total 54	NP (5–48)	22.5	Proximal realignment, distal realignment, or proximal-distal realignment; proximal-distal realignment and trochleoplasty 36%	6	NP	3 for all procedures	36% proximal realignment, 20% distal realignment, 32% proximal-distal realignment and trochleoplasty

NP not provided, *ROM* range of motion, *RTS* return to sport
[a]All data are given as provided in the study

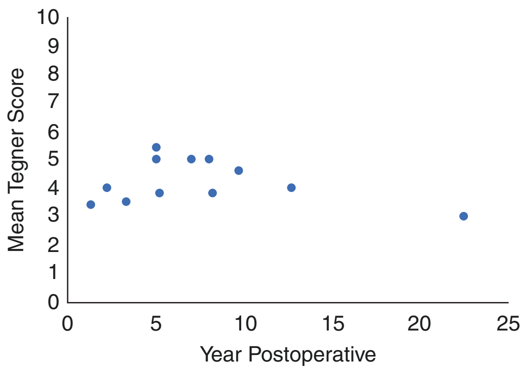


Fig. 28.5 Mean Tegner scores at follow-up after proximal and/or distal patellar realignment procedures in 13 studies

gies on a sports-specific return-to-play assessment" similar to the authors' anterior cruciate ligament patients. Contact sports involving extensive cutting and/or pivoting were prohibited until 9 months postoperatively. Overall, 70% returned to any sport and 54% returned to preinjury levels. The authors noted that 48 patients had participated in sports within 3 years of surgery and of these, 40 were able to return to at least one sport after surgery. Activities most commonly resumed included weightlifting, cycling, soccer, running, and yoga. There was no correlation between age, number of prior surgical procedures, smoking status, patellar Outerbridge grade, or the presence of trochlear lesions and the ability to RTS. There were no failures, although 47% had chronic pain and only 58% felt their knee was normal during sports.

Tjoumakaris et al. [71] followed 34 athletes (30 females, 4 males, mean age, 20 years) who underwent a Fulkerson procedure for a primary diagnosis of recurrent patellar instability. There were 14 high school, 12 collegiate, and 8 recreational athletes. Patients were allowed to RTS by 4–5 months after surgery if "adequate quadriceps strength and ROM" had been achieved. At follow-up, a mean of 3.8 years postoperatively, 97% had returned to their preinjury sport. The authors did not provide data related to any problems patients may have experienced while participating. The one patient who failed and had recurrent instability tested positive for Ehlers–Danlos syndrome.

28.4 Failure Rates

Twenty-three studies of MPFL reconstruction or repair reported no failures or recurrent dislocations resulting in the need for further surgery (Fig. 28.6). Hopper et al. [37] reported that all seven patients who had severe trochlear dysplasia (Dejour classification C and D) failed, suffering recurrent dislocations, compared with 7.4% of 54 patients with mild dysplasia. Xie et al. [40] found that patients in whom a semitendinosus MPFL reconstruction was augmented with polyester suture ($n = 42$) had a recurrent dislocation rate of just 2.4% compared with 23.3% of patients who did not have suture augmentation ($n = 43$). Zhao et al. [46] in a level 2 randomized study reported postoperative rates of redislocation and/or multiple episodes of instability of 9% after MPFL reconstruction ($n = 45$, mean age 25.0 ± 6.6) and 26% after medial retinaculum plication ($n = 43$, mean age 23.9 ± 5.8). At the 5-year follow-up, patients in the MPFL-reconstructed group had a significantly higher mean Tegner score (5.7 ± 1.7 and 4.0 ± 1.4, respectively; $P < 0.001$).

Four studies involving other proximal and/or distal procedures reported no failures or recurrent dislocations resulting in the need for further surgery. Sillanpaa et al. [5] reported that 14% of 21 knees failed after a Roux-Goldthwait procedure. Vivod et al. [72] followed 54 patients a

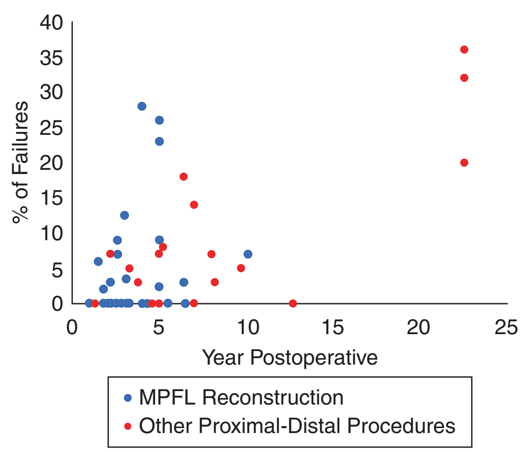


Fig. 28.6 Percentages of failures of MPFL reconstructions or repairs and other proximal-distal procedures (without MPFL reconstruction or repair) are shown

mean of 22.5 years postoperatively and reported failures (recurrent dislocations) in 36% after isolated proximal realignment, 32% after proximal-distal realignment, and 20% after isolated distal realignment. Kreuz et al. [65] followed three surgical groups in a nonrandomized study an average of 6.3 years postoperatively and found recurrent dislocations in 31% after isolated Green proximal realignment, in 29% after Green proximal and Roux-Goldthwait distal realignment, and in 12.5% after a combined proximal realignment and tubercle transfer ($P < 0.05$).

28.5 Advances in Operative Techniques for RTS

The RTS data summarized in this chapter reflect, for the most part, studies that failed to include modern objective testing of knee function, including strength and agility, as well as postoperative advanced neuromuscular retraining that is now recognized as vitally important after ACL surgery. Recent literature has demonstrated changes in surgical procedures recommended to correct patellofemoral instability that allows earlier restoration of ROM and muscle strength. These continued advances in both surgery and rehabilitation should, we believe, result in improved RTS data and lower failure rates. These include the following:

1. A better appreciation of the role of trochlear dysplasia which, when present, indicates a lack of a normal trochlear groove to provide patella stability and control patellar kinematics. Patients with trochlear dysplasia have a higher failure rate and rely to a greater extent on soft tissue ligament restraints and muscle control mechanisms. This also applies to patella alta cases, in which tibial tubercle distalization is required to position the patella within a normal patellar-trochlear relationship.
2. An understanding of the role of the MPFL in conjunction with other medial retinacular restraints (medial patellar meniscal and tibia restraints). MPFL surgery must restore a checkrein for abnormal lateral patellar translation, particularly from 0° to 20° of knee motion. The femoral attachment of the MPFL graft requires careful positioning from a proximal-to-distal direction to function at low knee flexion angles and avoid overtightening with knee flexion.
3. The indications for distal tibial tubercle medialization or elevation are now highly select and many knees do not require these procedures.
4. Proximal realignment procedures require early knee motion exercises to prevent abnormal scarring and disuse effects. For example, we reported that immediate ROM from 0° to 90° and full weight-bearing in extension is possible and encouraged immediately after surgery [73]. Previous rehabilitation protocols may have been overprotective regarding the allowance of immediate motion and weight-bearing.
5. Proximal MPFL grafts placed into the patella through drills holes risk patellar fracture. Docking of the graft at adjacent patella soft tissues avoids this complication. In the MPFL quadriceps turndown procedure advocated by the authors (Fig. 28.2) [1], the attachment of the quadriceps graft is performed entirely by soft tissue sutures at both the patella and femoral anatomic attachment sites, thereby avoiding the necessity for rigid fixation implants and their potential complications.

28.6 Postoperative Rehabilitation Concepts

Our postoperative rehabilitation protocol is summarized in Table 28.7. This protocol is used in patients undergoing proximal and distal extensor mechanism realignment procedures, with or without MPFL reconstruction. Patients are placed into a postoperative long-leg brace for the first 4 weeks. ROM exercises and patellar mobilization in superior-inferior and medial-lateral directions are begun immediately after surgery to prevent parapatellar contractures. The goal for the first week is to obtain 0–90° of motion. Knee flexion is gradually increased to 110° by the

Table 28.7 Noyes Knee Institute rehabilitation protocol for proximal-distal patellar realignment with and without MPFL reconstruction

	1–4 weeks	5–8 weeks	9–12 weeks	4–6 months	7–12 months
Brace					
Soft postoperative motion	X				
Patellar (optional, symptoms)		X	X	X	X
Range of motion minimum goals					
0–90° (week 1–2)	X				
0–110° (week 3–4)	X				
0–135°		X			
Weight-bearing					
Isolated MPFL reconstruction, 100%, crutch support as needed	X				
Concurrent tibial tubercle procedure 50% (weeks 1–2)	X				
Concurrent tibial tubercle procedure 100% (weeks 3–4)	X				
Patella mobilization	X	X			
Modalities					
Electrical muscle stimulation	X	X			
Biofeedback	X	X			
Pain/edema management (cryotherapy)	X	X	X	X	X
Stretching					
Hamstring, gastrocnemius-soleus, iliotibial band, quadriceps	X	X	X	X	X
Strengthening					
Quadriceps isometrics	X	X			
Straight leg raises (isolated MPFL reconstruction)	X				
Straight leg raises (concurrent tibial tubercle procedure)		X			
Active knee extension (with secure internal fixation tubercle)	X	X	X		
Closed-chain: toe raises, wall sits, mini-squats	X	X	X	X	
Knee flexion hamstring curls (90°)	X	X	X	X	X
Knee extension quadriceps (90–30°)	X	X	X	X	X
Hip abduction-adduction, multi-hip		X	X	X	X
Leg press (70–10°)		X	X	X	X
Balance/gait/proprioceptive training					
Weight-shifting, cup walking	X	X			
Mini-trampoline, BAPS, BBS (concurrent tibial tubercle procedure delay 4–6 weeks)	X	X	X	X	X
Conditioning					
Upper body weight training, core training	X	X	X	X	X
Upper body conditioner	X				
Stationary bicycling (high seat, low resistance)				X	X
Water walking		X	X	X	X
Swimming (kicking)			X	X	X
Walking		X	X	X	X
Ski machine (short stride, level, low resistance)		X	X	X	X
Running: straight			X[a]	X	X
Cutting: lateral carioca, figure eights				X[a]	X
Plyometric training, full sports				X[a]	X

BAPS Biomechanical Ankle Platform System (Camp, Jackson, MI), *BBS* Biodex Balance System (Biodex Medical Systems, Inc., Shirley, NY), *MPFL* medial patellofemoral ligament

[a]Only for patients with normal articular cartilage in the patellofemoral joint

fourth week and then a full motion of at least 135° is allowed by the eighth week. This limitation of flexion in the first 4 weeks is designed to protect the suture lines and the repair when a proximal realignment procedure is performed. The therapist should be aware of the potential for a knee motion complication and, if 0–110° is not obtained by the end of the fourth week, the patient should undergo a local anesthetic nerve block or a gentle ranging of motion under anesthesia as previously discussed. The early treatment and avoidance of an arthrofibrotic response to surgery are critical in these cases.

After isolated MPFL reconstruction, patients are allowed to bear 100% of their body weight with the knee at full extension using crutches for support. For patients who undergo a concurrent tibial tubercle medialization procedure, 50% weight-bearing is used for 2 weeks for protection and full weight-bearing is allowed by the fourth week.

Radiographs are taken the first and the fourth postoperative weeks to ensure adequate position and healing of the osteotomy. Weight-bearing may be delayed if problems are detected in bony healing or in quadriceps control. Flexibility exercises including stretching of hamstrings, gastrocnemius-soleus, quadriceps and iliotibial band are started the first week. The strengthening program for the quadriceps mechanism is begun during the first week and gradually progressed. Straight leg raises are allowed immediately after isolated MPFL reconstruction and at the fourth week after concurrent tibial tubercle procedures. Open kinetic chain exercises are begun immediately after isolated MPFL reconstruction but are delayed until the fourth to sixth week after concurrent tibial tubercle procedures at which time the osteotomy is usually healed.

Unfortunately, the majority of patients that undergo the operative procedures described in this chapter have marked joint deterioration from chronic patellofemoral malalignment or recurrent dislocation/subluxation episodes. In these patients, the goal of surgery is to return to light, low-impact activities only. In select patients (without articular cartilage damage) wishing to resume more strenuous activities, sports training is begun with a running program when the patient demonstrates at least 70% of the strength of the noninvolved limb for quadriceps and hamstrings on isometric testing, is at least 3 months postoperative, has normal patellar stability and tracking, and has no pain or joint effusion. Our running program is described in detail in Chap. 14. The program includes agility drills, cutting, and sharp directional change movement patterns. In select patients wishing to resume sports involving pivoting and cutting, a basic plyometric training program may be initiated upon completion of the running and agility program (see also Chap. 14). Final release to unrestricted sports is based on successful completion of training and achievement of normal indices shown in Table 28.8. Testing includes quadriceps and hamstrings isokinetic [78–88], isometric [89–91], or 1-repetition maximum bench press and leg press [92, 93]; two single-leg hops [74, 78, 80, 81, 94–97]; video drop-jump [75, 98–100], single-leg squat [101–104], and plant and cut [77, 105–107] tests. Other tests to consider before the patient is released to unrestricted athletic activities include the multistage fitness test to estimate VO_2max [108] and the 60-s sit-up test or other core strength measures [109].

A trial of function is encouraged in which the patient is monitored for knee swelling, pain, overuse symptoms, and instability episodes. Upon successful return to activity, the patient is encouraged to continue with a maintenance program. During the in-season, a conditioning program of two workouts a week is recommended. In the off-season or preseason, this program should be performed three times a week to maximize gains in flexibility, strength, and cardiovascular endurance.

Table 28.8 Criteria for release to unrestricted sports activities

Test	Criteria for release to sports
Range of knee motion	IKDC normal or nearly normal
Patellar pain and instability	None
Knee joint effusion	None
Isokinetic muscle (180°/s and 300°/s)	<10% deficit quadriceps and hamstrings compared with contralateral side
Isometric muscle (use if isokinetic equipment not available: portable fixed or hand-held dynamometer, quadriceps 60° flexion, hamstrings 60° or 90° flexion, 3 reps each, use mean)	<10% deficit quadriceps and hamstrings compared with contralateral side
1-repetition maximum bench press and leg press (use if isokinetic and isometric equipment not available)	<10% deficit quadriceps and hamstrings compared with contralateral side
Single-leg hops: any 2 (single hop, triple hop, triple crossover hop, timed hop) [74]	≤15% deficit lower limb symmetry on any two tests
Video drop-jump [75]	If software available: >60% normalized knee separation distance If software not available, subjective analysis landing position: no valgus, knees flexed for controlled landing
Video single-leg squat (5 reps) [76]	Subjective analysis: no knee valgus, medial-lateral movement, or pelvic tilt
Video plant and cut (patient runs 5 m to a spot designated on the floor with tape, plants on the reconstructed leg, and then performs a 45° cut) [77]	Subjective analysis: high hip and knee flexion, upright posture, no valgus collapse

IKDC International Knee Documentation Committee

References

1. Noyes FR, Barber-Westin SD. Operative options for extensor mechanism malalignment and patellar dislocation. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia, PA: Elsevier; 2017. p. 970–1013. https://doi.org/10.1016/b978-0-323-32903-3.00035-4.
2. Waterman BR, Belmont PJ Jr, Owens BD. Patellar dislocation in the United States: role of sex, age, race, and athletic participation. J Knee Surg. 2012;25(1):51–7.
3. Palmu S, Kallio PE, Donell ST, Helenius I, Nietosvaara Y. Acute patellar dislocation in children and adolescents: a randomized clinical trial. J Bone Joint Surg Am. 2008;90(3):463–70.
4. Hennrikus W, Pylawka T. Patellofemoral instability in skeletally immature athletes. Instr Course Lect. 2013;62:445–53.
5. Sillanpaa P, Mattila VM, Iivonen T, Visuri T, Pihlajamaki H. Incidence and risk factors of acute traumatic primary patellar dislocation. Med Sci Sports Exerc. 2008;40(4):606–11.
6. Smith TO, Davies L, Chester R, Clark A, Donell ST. Clinical outcomes of rehabilitation for patients following lateral patellar dislocation: a systematic review. Physiotherapy. 2010;96(4):269–81. https://doi.org/10.1016/j.physio.2010.02.006.
7. Maquet P. Valgus osteotomy for osteoarthritis of the knee. Clin Orthop Relat Res. 1976;120:143–8.
8. Trillat A, Dejour H, Couette A. Diagnosis and treatment of recurrent dislocations of the Patella. Rev Chir Orthop Reparatrice Appar Mot. 1964;50:813–24.
9. Fulkerson JP, Becker GJ, Meaney JA, Miranda M, Folcik MA. Anteromedial tibial tubercle transfer without bone graft. Am J Sports Med. 1990;18(5):490–6; discussion 496-497
10. Sanchis-Alfonso V. Guidelines for medial patellofemoral ligament reconstruction in chronic lateral patellar instability. J Am Acad Orthop Surg. 2014;22(3):175–82. https://doi.org/10.5435/JAAOS-22-03-175.
11. Matic GT, Magnussen RA, Kolovich GP, Flanigan DC. Return to activity after medial patellofemoral ligament repair or reconstruction. Arthroscopy. 2014;30(8):1018–25. https://doi.org/10.1016/j.arthro.2014.02.044.
12. Buckens CF, Saris DB. Reconstruction of the medial patellofemoral ligament for treatment of patellofemoral instability: a systematic review. Am J Sports Med. 2010;38(1):181–8. https://doi.org/10.1177/0363546509353132.
13. Bicos J, Fulkerson JP, Amis A. Current concepts review: the medial patellofemoral ligament. Am J Sports Med. 2007;35(3):484–92. https://doi.org/10.1177/0363546507299237.
14. Amis AA. Current concepts on anatomy and biomechanics of patellar stability. Sports Med Arthrosc. 2007;15(2):48–56.

15. Feller JA, Amis AA, Andrish JT, Arendt EA, Erasmus PJ, Powers CM. Surgical biomechanics of the patellofemoral joint. Arthroscopy. 2007;23(5):542–53.
16. Mihalko WM, Boachie-Adjei Y, Spang JT, Fulkerson JP, Arendt EA, Saleh KJ. Controversies and techniques in the surgical management of patellofemoral arthritis. Instr Course Lect. 2008;57:365–80.
17. Smith TO, Walker J, Russell N. Outcomes of medial patellofemoral ligament reconstruction for patellar instability: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2007;15(11):1301–14.
18. Fisher B, Nyland J, Brand E, Curtin B. Medial patellofemoral ligament reconstruction for recurrent patellar dislocation: a systematic review including rehabilitation and return-to-sports efficacy. Arthroscopy. 2010;26(10):1384–94. https://doi.org/10.1016/j.arthro.2010.04.005.
19. Singhal R, Rogers S, Charalambous CP. Double-bundle medial patellofemoral ligament reconstruction with hamstring tendon autograft and mediolateral patellar tunnel fixation: a meta-analysis of outcomes and complications. Bone Joint J. 2013;95-B(7):900–5. https://doi.org/10.1302/0301-620X.95B7.31417.
20. Vavken P, Wimmer MD, Camathias C, Quidde J, Valderrabano V, Pagenstert G. Treating patella instability in skeletally immature patients. Arthroscopy. 2013;29(8):1410–22. https://doi.org/10.1016/j.arthro.2013.03.075.
21. Zaman S, White A, Shi WJ, Freedman KB, Dodson CC. Return-to-play guidelines after medial patellofemoral ligament surgery for recurrent patellar instability: a systematic review. Am J Sports Med. 2018;46(10):2530–9. https://doi.org/10.1177/0363546517713663.
22. Menetrey J, Putman S, Gard S. Return to sport after patellar dislocation or following surgery for patellofemoral instability. Knee Surg Sports Traumatol Arthrosc. 2014;22(10):2320–6. https://doi.org/10.1007/s00167-014-3172-5.
23. Carnesecchi O, Philippot R, Boyer B, Farizon F, Edouard P. Recovery of gait pattern after medial patellofemoral ligament reconstruction for objective patellar instability. Knee Surg Sports Traumatol Arthrosc. 2016;24(1):123–8. https://doi.org/10.1007/s00167-014-3347-0.
24. Nelitz M, Dreyhaupt J, Reichel H, Woelfle J, Lippacher S. Anatomic reconstruction of the medial patellofemoral ligament in children and adolescents with open growth plates: surgical technique and clinical outcome. Am J Sports Med. 2013;41(1):58–63. https://doi.org/10.1177/0363546512463683.
25. Drez D Jr, Edwards TB, Williams CS. Results of medial patellofemoral ligament reconstruction in the treatment of patellar dislocation. Arthroscopy. 2001;17(3):298–306.
26. Nelitz M, Dreyhaupt J, Lippacher S. Combined trochleoplasty and medial patellofemoral ligament reconstruction for recurrent patellar dislocations in severe trochlear dysplasia: a minimum 2-year follow-up study. Am J Sports Med. 2013;41(5):1005–12. https://doi.org/10.1177/0363546513478579.
27. Panni AS, Alam M, Cerciello S, Vasso M, Maffulli N. Medial patellofemoral ligament reconstruction with a divergent patellar transverse 2-tunnel technique. Am J Sports Med. 2011;39(12):2647–55. https://doi.org/10.1177/0363546511420079.
28. Lippacher S, Dreyhaupt J, Williams SR, Reichel H, Nelitz M. Reconstruction of the medial patellofemoral ligament: clinical outcomes and return to sports. Am J Sports Med. 2014;42(7):1661–8. https://doi.org/10.1177/0363546514529640.
29. Camp CL, Krych AJ, Dahm DL, Levy BA, Stuart MJ. Medial patellofemoral ligament repair for recurrent patellar dislocation. Am J Sports Med. 2010;38(11):2248–54. https://doi.org/10.1177/0363546510376230.
30. Ahmad CS, Stein BE, Matuz D, Henry JH. Immediate surgical repair of the medial patellar stabilizers for acute patellar dislocation. A review of eight cases. Am J Sports Med. 2000;28(6):804–10.
31. Ronga M, Oliva F, Longo UG, Testa V, Capasso G, Maffulli N. Isolated medial patellofemoral ligament reconstruction for recurrent patellar dislocation. Am J Sports Med. 2009;37(9):1735–42. https://doi.org/10.1177/0363546509333482.
32. Mariani PP, Liguori L, Cerullo G, Iannella G, Floris L. Arthroscopic patellar reinsertion of the MPFL in acute patellar dislocations. Knee Surg Sports Traumatol Arthrosc. 2011;19(4):628–33. https://doi.org/10.1007/s00167-010-1315-x.
33. Feller JA, Richmond AK, Wasiak J. Medial patellofemoral ligament reconstruction as an isolated or combined procedure for recurrent patellar instability. Knee Surg Sports Traumatol Arthrosc. 2014;22(10):2470–6. https://doi.org/10.1007/s00167-014-3132-0.
34. Wagner D, Pfalzer F, Hingelbaum S, Huth J, Mauch F, Bauer G. The influence of risk factors on clinical outcomes following anatomical medial patellofemoral ligament (MPFL) reconstruction using the gracilis tendon. Knee Surg Sports Traumatol Arthrosc. 2013;21(2):318–24. https://doi.org/10.1007/s00167-012-2015-5.
35. Ambrozic B, Novak S. The influence of medial patellofemoral ligament reconstruction on clinical results and sports activity level. Phys Sportsmed. 2016;44(2):133–40. https://doi.org/10.1080/00913847.2016.1148561.
36. Howells NR, Barnett AJ, Ahearn N, Ansari A, Eldridge JD. Medial patellofemoral ligament reconstruction: a prospective outcome assessment of a large single centre series. J Bone Joint Surg. 2012;94(9):1202–8. https://doi.org/10.1302/0301-620X.94B9.28738.
37. Hopper GP, Leach WJ, Rooney BP, Walker CR, Blyth MJ. Does degree of trochlear dysplasia and position of femoral tunnel influence outcome after medial patellofemoral ligament reconstruction? Am J Sports Med. 2014;42(3):716–22. https://doi.org/10.1177/0363546513518413.

38. Tompkins M, Kuenze CM, Diduch DR, Miller MD, Milewski MD, Hart JP. Clinical and functional outcomes following primary repair versus reconstruction of the medial patellofemoral ligament for recurrent patellar instability. J Sports Med (Hindawi Publ Corp). 2014;2014:702358. https://doi.org/10.1155/2014/702358.
39. Lim AK, Chang HC, Hui JH. Recurrent patellar dislocation: reappraising our approach to surgery. Ann Acad Med Singap. 2008;37(4):320–3.
40. Xie G, Zhao J, Huangfu X, He Y. Medial patellofemoral ligament reconstruction using semitendinosus tendons: polyester suture augmentation versus non-augmentation. Am J Sports Med. 2012;40(6):1365–74. https://doi.org/10.1177/0363546512441324.
41. Blond L, Haugegaard M. Combined arthroscopic deepening trochleoplasty and reconstruction of the medial patellofemoral ligament for patients with recurrent patella dislocation and trochlear dysplasia. Knee Surg Sports Traumatol Arthrosc. 2014;22(10):2484–90. https://doi.org/10.1007/s00167-013-2422-2.
42. Banke IJ, Kohn LM, Meidinger G, Otto A, Hensler D, Beitzel K, Imhoff AB, Schottle PB. Combined trochleoplasty and MPFL reconstruction for treatment of chronic patellofemoral instability: a prospective minimum 2-year follow-up study. Knee Surg Sports Traumatol Arthrosc. 2014;22(11):2591–8. https://doi.org/10.1007/s00167-013-2603-z.
43. Li J, Li Y, Wei J, Wang J, Gao S, Shen Y. A simple technique for reconstruction of medial patellofemoral ligament with bone-fascia tunnel fixation at the medial margin of the patella: a 6-year-minimum follow-up study. J Orthop Surg Res. 2014;9:66. https://doi.org/10.1186/s13018-014-0066-7.
44. Berruto M, Ferrua P, Uboldi F, Usellini E, Gala L, Tassi A, Marelli B. Medial patellofemoral ligament reconstruction with bioactive synthetic ligament is an option. A 3-year follow-up study. Knee Surg Sports Traumatol Arthrosc. 2014;22(10):2419–25. https://doi.org/10.1007/s00167-014-2970-0.
45. Calanna F, Pulici L, Carimati G, Quaglia A, Volpi P. Medial patello-femoral ligament (MPFL) reconstruction using suture anchors fixation: preliminary results. Muscles Ligaments Tendons J. 2016;6(1):64–70. https://doi.org/10.11138/mltj/2016.6.1.064.
46. Zhao J, Huangfu X, He Y. The role of medial retinaculum plication versus medial patellofemoral ligament reconstruction in combined procedures for recurrent patellar instability in adults. Am J Sports Med. 2012;40(6):1355–64. https://doi.org/10.1177/0363546512439193.
47. Ahmad CS, Brown GD, Stein BS. The docking technique for medial patellofemoral ligament reconstruction: surgical technique and clinical outcome. Am J Sports Med. 2009;37(10):2021–7. https://doi.org/10.1177/0363546509336261.
48. Csintalan RP, Latt LD, Fornalski S, Raiszadeh K, Inacio MC, Fithian DC. Medial patellofemoral ligament (MPFL) reconstruction for the treatment of patellofemoral instability. J Knee Surg. 2014;27(2):139–46. https://doi.org/10.1055/s-0033-1360652.
49. Becher C, Kley K, Lobenhoffer P, Ezechieli M, Smith T, Ostermeier S. Dynamic versus static reconstruction of the medial patellofemoral ligament for recurrent lateral patellar dislocation. Knee Surg Sports Traumatol Arthrosc. 2014;22(10):2452–7. https://doi.org/10.1007/s00167-014-3020-7.
50. Steiner TM, Torga-Spak R, Teitge RA. Medial patellofemoral ligament reconstruction in patients with lateral patellar instability and trochlear dysplasia. Am J Sports Med. 2006;34(8):1254–61.
51. Hinterwimmer S, Imhoff AB, Minzlaff P, Saier T, Rosenstiel N, Hawe W, Feucht MJ. Anatomical two-bundle medial patellofemoral ligament reconstruction with hardware-free patellar graft fixation: technical note and preliminary results. Knee Surg Sports Traumatol Arthrosc. 2013;21(9):2147–54. https://doi.org/10.1007/s00167-013-2498-8.
52. Ma LF, Wang F, Chen BC, Wang CH, Zhou JW, Wang HY. Medial retinaculum plasty versus medial patellofemoral ligament reconstruction for recurrent patellar instability in adults: a randomized controlled trial. Arthroscopy. 2013;29(5):891–7. https://doi.org/10.1016/j.arthro.2013.01.030.
53. Song SY, Kim IS, Chang HG, Shin JH, Kim HJ, Seo YJ. Anatomic medial patellofemoral ligament reconstruction using patellar suture anchor fixation for recurrent patellar instability. Knee Surg Sports Traumatol Arthrosc. 2014;22(10):2431–7. https://doi.org/10.1007/s00167-013-2730-6.
54. Kohn LM, Meidinger G, Beitzel K, Banke IJ, Hensler D, Imhoff AB, Schottle PB. Isolated and combined medial patellofemoral ligament reconstruction in revision surgery for patellofemoral instability: a prospective study. Am J Sports Med. 2013;41(9):2128–35. https://doi.org/10.1177/0363546513498572.
55. Suganuma J, Mochizuki R, Sugiki T, Inoue Y, Kitamura K, Akutsu S, Ono H. Reconstruction of the medial patellofemoral ligament using a synthetic graft with arthroscopic control of patellofemoral congruence. Arthroscopy. 2016;32(11):2259–68. https://doi.org/10.1016/j.arthro.2016.02.004.
56. Matthews JJ, Schranz P. Reconstruction of the medial patellofemoral ligament using a longitudinal patellar tunnel technique. Int Orthop. 2010;34(8):1321–5. https://doi.org/10.1007/s00264-009-0918-7.
57. Christiansen SE, Jacobsen BW, Lund B, Lind M. Reconstruction of the medial patellofemoral ligament with gracilis tendon autograft in transverse patellar drill holes. Arthroscopy. 2008;24(1):82–7.
58. Sillanpaa P, Mattila VM, Visuri T, Maenpaa H, Pihlajamaki H. Ligament reconstruction versus distal realignment for patellar dislocation. Clin Orthop Relat Res. 2008;466(6):1475–84. https://doi.org/10.1007/s11999-008-0207-6.
59. Barber FA, McGarry JE. Elmslie-Trillat procedure for the treatment of recurrent patellar instability. Arthroscopy. 2008;24(1):77–81.

60. Berruto M, Uboldi FM, Ferrua P, Vergottini G, Manunta A. Surgical treatment of objective patellar instability: long-term results. Joints. 2018;6(1):33–6. https://doi.org/10.1055/s-0038-1636949.
61. Carney JR, Mologne TS, Muldoon M, Cox JS. Long-term evaluation of the Roux-Elmslie-Trillat procedure for patellar instability: a 26-year follow-up. Am J Sports Med. 2005;33(8):1220–3. https://doi.org/10.1177/0363546504272686.
62. Endres S, Wilke A. A 10 year follow-up study after roux-elmslie-Trillat treatment for cases of patellar instability. BMC Musculoskelet Disord. 2011;12:48. https://doi.org/10.1186/1471-2474-12-48.
63. Karataglis D, Green MA, Learmonth DJ. Functional outcome following modified elmslie-Trillat procedure. Knee. 2006;13(6):464–8. https://doi.org/10.1016/j.knee.2006.08.004.
64. Kraus T, Lidder S, Svehlik M, Rippel K, Schneider F, Eberl R, Linhart W. Patella re-alignment in children with a modified Grammont technique. Acta Orthop. 2012;83(5):504–10. https://doi.org/10.3109/17453674.2012.736168.
65. Kreuz PC, Peterson L, van der Werf-Grohmann N, Vohrer M, Schwering L. Clinical and electromyographic results of proximal and distal realignment procedures in young patients with recurrent patellar dislocations. Am J Sports Med. 2013;41(7):1621–8. https://doi.org/10.1177/0363546513488869.
66. Liu JN, Wu HH, Garcia GH, Kalbian IL, Strickland SM, Shubin Stein BE. Return to sports after tibial tubercle osteotomy for patellofemoral pain and osteoarthritis. Arthroscopy. 2018;34(4):1022–9. https://doi.org/10.1016/j.arthro.2017.09.021.
67. Luhmann SJ, O'Donnell JC, Fuhrhop S. Outcomes after patellar realignment surgery for recurrent patellar instability dislocations: a minimum 3-year follow-up study of children and adolescents. J Pediatr Orthop. 2011;31(1):65–71. https://doi.org/10.1097/BPO.0b013e318202c42d.
68. Marcacci M, Zaffagnini S, Lo Presti M, Vascellari A, Iacono F, Russo A. Treatment of chronic patellar dislocation with a modified Elmslie-Trillat procedure. Arch Orthop Trauma Surg. 2004;124(4):250–7. https://doi.org/10.1007/s00402-003-0511-2.
69. Rillmann P, Dutly A, Kieser C, Berbig R. Modified elmslie-Trillat procedure for instability of the patella. Knee Surg Sports Traumatol Arthrosc. 1998;6(1):31–5. https://doi.org/10.1007/s001670050069.
70. Sillanpaa PJ, Mattila VM, Maenpaa H, Kiuru M, Visuri T, Pihlajamaki H. Treatment with and without initial stabilizing surgery for primary traumatic patellar dislocation. A prospective randomized study. J Bone Joint Surg Am. 2009;91(2):263–73. https://doi.org/10.2106/JBJS.G.01449.
71. Tjoumakaris FP, Forsythe B, Bradley JP. Patellofemoral instability in athletes: treatment via modified Fulkerson osteotomy and lateral release. Am J Sports Med. 2010;38(5):992–9. https://doi.org/10.1177/0363546509357682.
72. Vivod G, Verdonk P, Drobnic M. Long-term clinical and radiographic outcome of patello-femoral realignment procedures: a minimum of 15-year follow-up. Knee Surg Sports Traumatol Arthrosc. 2014;22(11):2747–55. https://doi.org/10.1007/s00167-013-2637-2.
73. Parikh SN, Albright J, Noyes FR. Proximal and distal extensor mechanism realignment: the surgical technique. Tech Knee Surg. 2006;5:27–38.
74. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med. 1991;19(5):513–8.
75. Noyes FR, Barber-Westin SD, Fleckenstein C, Walsh C, West J. The drop-jump screening test: difference in lower limb control by gender and effect of neuromuscular training in female athletes. Am J Sports Med. 2005;33(2):197–207.
76. Ireland ML, Bolgla LA, Noehren B. Gender differences in core strength and lower extremity function during static and dynamic single-leg squat tests. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete. Causes, impacts, and conditioning programs. 2nd ed. Berlin Heidelberg, New York: Springer-Verlag; 2018. p. 239–57.
77. Pollard CD, Sigward SM, Powers CM. Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. Clin J Sport Med. 2007;17(1):38–42. https://doi.org/10.1097/JSM.0b013e3180305de8.
78. Zaffagnini S, Bruni D, Marcheggiani Muccioli GM, Bonanzinga T, Lopomo N, Bignozzi S, Marcacci M. Single-bundle patellar tendon versus non-anatomical double-bundle hamstrings ACL reconstruction: a prospective randomized study at 8-year minimum follow-up. Knee Surg Sports Traumatol Arthrosc. 2011;19(3):390–7. https://doi.org/10.1007/s00167-010-1225-y.
79. Choi NH, Lee JH, Son KM, Victoroff BN. Tibial tunnel widening after anterior cruciate ligament reconstructions with hamstring tendons using rigidfix femoral fixation and intrafix tibial fixation. Knee Surg Sports Traumatol Arthrosc. 2010;18(1):92–7. https://doi.org/10.1007/s00167-009-0951-5.
80. Landes S, Nyland J, Elmlinger B, Tillett E, Caborn D. Knee flexor strength after ACL reconstruction: comparison between hamstring autograft, tibialis anterior allograft, and non-injured controls. Knee Surg Sports Traumatol Arthrosc. 2010;18(3):317–24. https://doi.org/10.1007/s00167-009-0931-9.
81. Hartigan EH, Axe MJ, Snyder-Mackler L. Time line for noncopers to pass return-to-sports criteria after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2010;40(3):141–54. https://doi.org/10.2519/jospt.2010.3168.
82. Isberg J, Faxen E, Brandsson S, Eriksson BI, Karrholm J, Karlsson J. Early active extension after anterior cruciate ligament reconstruction does not result in increased laxity of the knee. Knee Surg

Sports Traumatol Arthrosc. 2006;14(11):1108–15. https://doi.org/10.1007/s00167-006-0138-2.
83. Sajovic M, Vengust V, Komadina R, Tavcar R, Skaza K. A prospective, randomized comparison of semitendinosus and gracilis tendon versus patellar tendon autografts for anterior cruciate ligament reconstruction: five-year follow-up. Am J Sports Med. 2006;34(12):1933–40.
84. Poehling GG, Curl WW, Lee CA, Ginn TA, Rushing JT, Naughton MJ, Holden MB, Martin DF, Smith BP. Analysis of outcomes of anterior cruciate ligament repair with 5-year follow-up: allograft versus autograft. Arthroscopy. 2005;21(7):774–85.
85. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. Sports Med (Auckland, NZ). 2004;34(4):269–80.
86. Beynnon BD, Johnson RJ, Fleming BC, Kannus P, Kaplan M, Samani J, Renstr m P. Anterior cruciate ligament replacement: comparison of bone-patellar tendon-bone grafts with two-strand hamstring grafts: a prospective, randomized study. J Bone Joint Surg Am. 2002;84-A(9):PG-1503-13.
87. Henriksson M, Rockborn P, Good L. Range of motion training in brace vs. plaster immobilization after anterior cruciate ligament reconstruction: a prospective randomized comparison with a 2-year follow-up. Scand J Med Sci Sports. 2002;12(2):73–80.
88. Moller E, Forssblad M, Hansson L, Wange P, Weidenhielm L. Bracing versus nonbracing in rehabilitation after anterior cruciate ligament reconstruction: a randomized prospective study with 2-year follow-up. Knee Surg Sports Traumatol Arthrosc. 2001;9(2):102–8.
89. Stark T, Walker B, Phillips JK, Fejer R, Beck R. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. PM R. 2011;3(5):472–9. https://doi.org/10.1016/j.pmrj.2010.10.025.
90. Toonstra J, Mattacola CG. Test-retest reliability and validity of isometric knee-flexion and -extension measurement using 3 methods of assessing muscle strength. J Sport Rehabil. 2013;22(7)
91. Whiteley R, Jacobsen P, Prior S, Skazalski C, Otten R, Johnson A. Correlation of isokinetic and novel hand-held dynamometry measures of knee flexion and extension strength testing. J Sci Med Sport. 2012;15(5):444–50. https://doi.org/10.1016/j.jsams.2012.01.003.
92. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, Newton RU, Triplett NT, Dziados JE. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. J Appl Physiol. 1995;78(3):976–89.
93. Reiman MP, Manske RC. Functional testing in human performance. Champaign: Human Kinetics; 2009.
94. Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. Clin Orthop Relat Res. 1990;255(255):204–14.
95. Barrett GR, Luber K, Replogle WH, Manley JL. Allograft anterior cruciate ligament reconstruction in the young, active patient: tegner activity level and failure rate. Arthroscopy. 2010;26(12):1593–601. https://doi.org/10.1016/j.arthro.2010.05.014.
96. Logerstedt D, Grindem H, Lynch A, Eitzen I, Engebretsen L, Risberg MA, Axe MJ, Snyder-Mackler L. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo ACL cohort study. Am J Sports Med. 2012;40(10):2348–56. https://doi.org/10.1177/0363546512457551.
97. Logerstedt D, Di Stasi S, Grindem H, Lynch A, Eitzen I, Engebretsen L, Risberg MA, Axe MJ, Snyder-Mackler L. Self-reported knee function can identify athletes who fail return-to-activity criteria up to 1 year after anterior cruciate ligament reconstruction: a Delaware-Oslo ACL cohort study. J Orthop Sports Phys Ther. 2014;44(12):914–23. https://doi.org/10.2519/jospt.2014.4852.
98. Sigward SM, Havens KL, Powers CM. Knee separation distance and lower extremity kinematics during a drop land: implications for clinical screening. J Athl Train. 2011;46(5):471–5.
99. Nilstad A, Andersen TE, Kristianslund E, Bahr R, Myklebust G, Steffen K, Krosshaug T. Physiotherapists can identify female football players with high knee valgus angles during vertical drop jumps using real-time observational screening. J Orthop Sports Phys Ther. 2014;44(5):358–65. https://doi.org/10.2519/jospt.2014.4969.
100. Pollard CD, Sigward SM, Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. Clin Biomech (Bristol, Avon). 2010;25(2):142–6. https://doi.org/10.1016/j.clinbiomech.2009.10.005.
101. Ireland ML, Durbin T, Bolgla LA. Gender differences in core strength and lower extremity function during the single-leg squat test. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete: causes, impacts, and conditioning programs. Berlin Heidelberg: Springer-Verlag; 2012. p. 203–19.
102. Ageberg E, Bennell KL, Hunt MA, Simic M, Roos EM, Creaby MW. Validity and inter-rater reliability of medio-lateral knee motion observed during a single-limb mini squat. BMC Musculoskelet Disord. 2010;11:265. https://doi.org/10.1186/1471-2474-11-265.
103. Claiborne TL, Armstrong CW, Gandhi V, Pincivero DM. Relationship between hip and knee strength and knee valgus during a single leg squat. J Appl Biomech. 2006;22(1):41–50.
104. Ireland ML. The female ACL: why is it more prone to injury? Orthop Clin North Am. 2002;33(4):637–51.
105. Cortes N, Onate J, Van Lunen B. Pivot task increases knee frontal plane loading compared with sidestep

and drop-jump. J Sports Sci. 2011;29(1):83–92. https://doi.org/10.1080/02640414.2010.523087.

106. Jones PA, Herrington LC, Munro AG, Graham-Smith P. Is there a relationship between landing, cutting, and pivoting tasks in terms of the characteristics of dynamic valgus? Am J Sports Med. 2014;42(9):2095–102. https://doi.org/10.1177/0363546514539446.
107. Nagano Y, Ida H, Akai M, Fukubayashi T. Biomechanical characteristics of the knee joint in female athletes during tasks associated with anterior cruciate ligament injury. Knee. 2009;16(2):153–8. https://doi.org/10.1016/j.knee.2008.10.012.
108. Ramsbottom R, Brewer J, Williams C. A progressive shuttle run test to estimate maximal oxygen uptake. Br J Sports Med. 1988;22(4):141–4.
109. Okada T, Huxel KC, Nesser TW. Relationship between core stability, functional movement, and performance. J Strength Cond Res. 2011;25(1):252–61. https://doi.org/10.1519/JSC.0b013e3181b22b3e.

29 Return to Sport After Cartilage Procedures

Taylor M. Southworth, Neal B. Naveen, Tracy M. Tauro, Ian J. Dempsey, Jorge Chahla, and Brian J. Cole

29.1 Introduction

There are an estimated 30,000–100,000 cartilage restoration procedures performed annually in the USA, a number that is growing 5% annually [1, 2]. Focal cartilage defects have been identified in about 60% of those undergoing arthroscopy in the general population [3, 4]. As these defects can be symptomatic and interfere with both athletics and basic activities of daily living, a variety of cartilage restoration procedures can be performed to treat symptoms. The current surgical treatment options for focal chondral defects include arthroscopic debridement, marrow stimulation techniques such as microfracture (with or without adjuncts), restorative procedures such as matrix-induced autologous chondrocyte implantation (MACI), osteochondral allografts (OCA), and osteochondral autograft transplant (OAT) with the possibility of adjunct orthobiologics such as platelet-rich plasma (PRP) or bone marrow aspirate concentrate [5–7].

Athletic sports participation is a major contributor of microtrauma to the articular surface of the knee due to the significant load-bearing stress that occurs during play [8, 9]. Focal chondral defects have been reported in up to 89% of high-level athletes, with full-thickness defects being reported in 36% of patients [10, 11]. Focal defects have also been noted in up to 50% of athletes undergoing anterior cruciate ligament reconstruction [12, 13]. Athletes are not limited to lesions of this origin; however, as other etiologies include osteochondritis dissecans and early degenerative changes. Over time these lesions may progress in size and depth, becoming more symptomatic, and eventually progressing to osteoarthritis [14–20]. In athletes specifically, it has been noted that there is a 12-fold increase in the risk for developing knee osteoarthritis [21–24]. The rise in cartilage restoration procedures is suggested to stem not only from increased treatment options but also from an increased prevalence of lesions in patients as athletic sports participation has been on the rise [12, 25]. Additionally, in this subset of patients, an important priority is a timely and safe return to sport (RTS). Therefore, RTS expectations after cartilage restoration procedures should be a critical point of emphasis between the physician and the athlete.

In the athletic population, it is essential to acknowledge the importance of RTS at preinjury levels in a timely fashion while minimizing the

T. M. Southworth · N. B. Naveen (✉) · T. M. Tauro
I. J. Dempsey · J. Chahla · B. J. Cole
Department of Orthopaedics Surgery, Rush University Medical Center, Chicago, IL, USA
e-mail: nnaveen@iu.edu; brian.cole@rushortho.com; Ian_J_Dempsey@rush.edu

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_29

risk of reinjury or the need for future surgery. This involves choosing the appropriate treatment option for the lesion characteristics and the patient's postoperative goals and rehabilitation timeline. For each procedure, it is recommended that after formal physical therapy, patients undergo sport-specific rehabilitation in order to reduce the risk of reinjury and ensure patients are able to complete all of the necessary movements required for safe return to their specific sport. Della Villa et al. found that after undergoing autologous chondrocyte implantation (ACI), athletes who trained with an on-field sport-specific rehabilitation program showed a quicker RTS as well as a quicker return to preinjury level of play compared with controls [26]. Ultimately, RTS after cartilage restoration is a multifactorial decision individualized for each patient. Previous studies have shown promising outcomes in regard to RTS. For example, Messner et al. evaluated athletes with isolated, severe chondral damage and found that 75% initially RTS after undergoing a cartilage restoration procedure. The study reported that although there was a significant decrease in sport involvement 14 years after surgery, the majority of patients continued to live an active lifestyle [27].

In the authors' (BJC) practice, the preferred algorithm for determining the definitive operative treatment for chondral defects is shown in Fig. 29.1 [28]. Debridement of the lesion regardless of size is always an acceptable option as a starting approach because it allows for a better understanding of the defect characteristics and

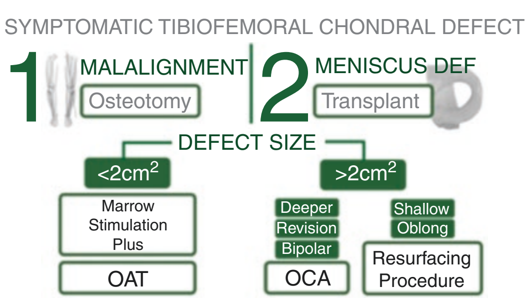


Fig. 29.1 The authors' (BJC) treatment algorithm for treating focal chondral defects. *DEF* deficient, *OAT* osteochondral autograft transplantation, *OCA* osteochondral allograft transplantation

the overall status of the knee joint with a minimally invasive approach, while also allowing some patients to achieve temporary symptom relief [29]. In lesions that are <2 cm^2 in patients with a low-demand lifestyle, the treatment options are debridement alone or debridement with marrow stimulation. In the same size lesion in a high-demand patient, the treatment options include OAT in addition to debridement and marrow stimulation. Similarly, in patients with lesions >2 cm^2 with a low-demand lifestyle, the treatment options include MACI as well as the previously mentioned techniques. In high-demand patients with large lesions, OCA and MACI are the optimal treatments. MACI requires the subchondral bone to be otherwise intact without overt pathology.

29.2 Microfracture

Marrow stimulation techniques such as microfracture (Fig. 29.2) violate the subchondral bone in order to stimulate fibrocartilage fill in the defect [30]. After debridement of the defect to achieve stable vertical edges, microfracture holes are created along the periphery of the defect prior to moving more centrally. Historically, microfracture has been done using an arthroscopic awl to create microfracture pores [31]. More recently, mechanical drills have been used to create microfracture holes, such as in Fig. 29.2. Microfracture can also be augmented with scaffolds or dehydrated cartilage allograft with platelet-rich plasma or bone marrow aspirate concentrate [32, 33]. Microfracture is primarily recommended for patients with chondral lesions <2 cm^2 with low to moderate levels of physical demand and minimal to no bone involvement [28]. The postoperative rehabilitation protocol is summarized in Table 29.1. Functional activities can begin around 6 months postoperatively with RTS and impact after about 8 months.

In a systematic review of 821 athletes who underwent microfracture, Mithoefer et al. reported that RTS was achieved in 66% ±6% (range, 44–100%) at an average of 8 ±1 months (range, 2–16 months), with 67% ±5% (range,

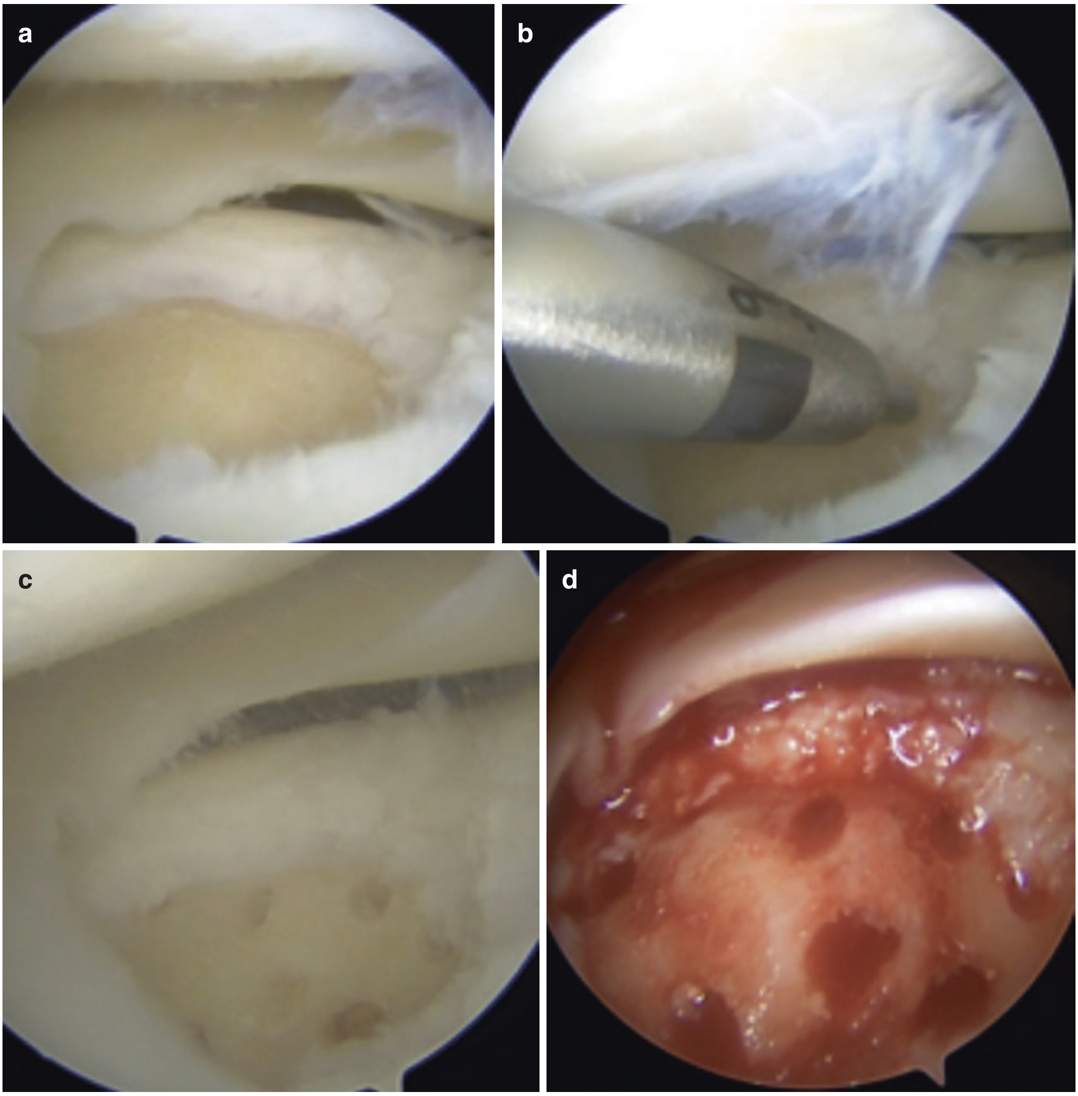


Fig. 29.2 Microfracture of a lateral tibial plateau (LTP) focal chondral lesion. (**a**) LTP focal chondral defect prepared with vertical stable borders (as seen from the anteromedial portal). (**b**) The defect is microdrilled using a mechanical drill for microfracture of the LTP defect. (**c**) LTP chondral defect after microfracture. (**d**) LTP defect after microfracture-stimulated bleeding (tourniquet was released)

50–100%) of patients returning to preinjury levels. Furthermore, 2–5 years after microfracture, the same study found that 49% ± 9% (range, 18–71%) of patients continued sports participation at the preinjury level. The authors noted that after the initial improvement in activity scores, 42% of the studies showed decreasing activity scores in 47–80% of patients after 2–5 years, suggesting that microfracture can return a moderate percentage of athletes to sport, but this number declines after 2 years postoperatively [24].

In order to maximize safe RTS after microfracture, it is important to use careful patient selection for the procedure. For example, in a prospective evaluation of athletes undergoing microfracture, Mithoefer et al. found that while 65% of patients under the age of 40 were able to RTS, only 20% of those over the age of 40 were able to RTS [34]. Furthermore, multiple studies

Table 29.1 Postoperative rehabilitation protocol for cartilage procedures of the tibiofemoral compartment

Weight-bearing	
Weeks 0–6	Non-weight-bearing
Weeks 6–8	Advance 25% weekly until full weight-bearing
Week 8	Full weight-bearing
Brace	
Weeks 0–2	Locked in full extension at all times, off for CPM and exercise only
Week 2	Discontinue brace
Range of motion	
Weeks 0–6	Use CPM for 6 h/day, beginning at 0–40° and advancing 5–10° daily as tolerated
Weeks 6–8	Full ROM
Exercises	
Weeks 0–2	Quadriceps sets, single-leg raises, calf pumps, passive leg hangs to 90°
Weeks 2–6	Passive ROM and active ROM to tolerance, quadriceps, hamstring and glut sets, side-lying hip, and core exercises
Weeks 6–8	Advance exercises from weeks 2 to 6
Weeks 8–12	Gait training, wall sits, shuttle, mini-squats, toe raises, unilateral stance activities, and balance training
Week 12–6 months	Maximize core/glutes exercises, pelvic stability, eccentric hamstrings May advance to pool, elliptical, and bike as tolerated
6–12 months	Advance functional activities, return to sport-specific activity, and impact when cleared by physician after 8 months

CPM continuous passive motion, *ROM* range of motion

have reported that lesion size >2 cm^2 correlates with lower RTS rates and worse outcomes than those defects <2 cm^2 [34, 35]. The authors also reported that symptom duration longer than 1 year prior to microfracture allowed a RTS rate of only 14%, whereas those with symptoms less than 1 year returned to sport at a rate of 67% [34]. Additionally, microfracture as a first-line procedure showed higher RTS rates than in patients who had undergone previous surgery [34, 36]. BMI less than 30 was also associated with better outcomes [37]. On an encouraging note for athletes, those who have higher preoperative activity level scores were found to return to higher activity levels postoperatively [34, 38, 39].

Overall, in the appropriately selected patient population, microfracture can provide the ability to RTS; however, this should be weighed against newer cartilage restoration procedures that may demonstrate improved RTS. In a meta-analysis of 44 studies evaluating RTS with a minimum 2-year follow-up after microfracture, OAT, OCA, and ACI, Krych et al. found that microfracture reported the lowest RTS outcomes, with a rate of 58% [40]. Similarly, Mithoefer et al. found that 44% of athletes were able to return to high-impact activity, but only 57% of those were able to return to their preinjury level of play [34]. The data on microfracture suggests that while it can provide immediate relief and quick RTS, it is indicated only in a specific patient population, has lower RTS rates than other cartilage restoration procedures, and the positive outcomes may deteriorate after 2 years. Importantly, in the event that a revision surgery is indicated, Minas et al. found that patients who undergo ACI after failed microfracture are 2.5 times more likely to fail ACI than those with untreated lesions [41].

29.3 MACI

If a full-thickness, isolated defect is >2 cm^2 and there is no subchondral involvement, the ACI technique may be used (Fig. 29.3). There are three different generations of ACI, with the most recent utilizing a chondroinductive matrix to culture the cells. MACI, or third-generation ACI, involves a two-step surgical process which includes taking a biopsy of cartilage from the intercondylar notch and culturing the cells on a

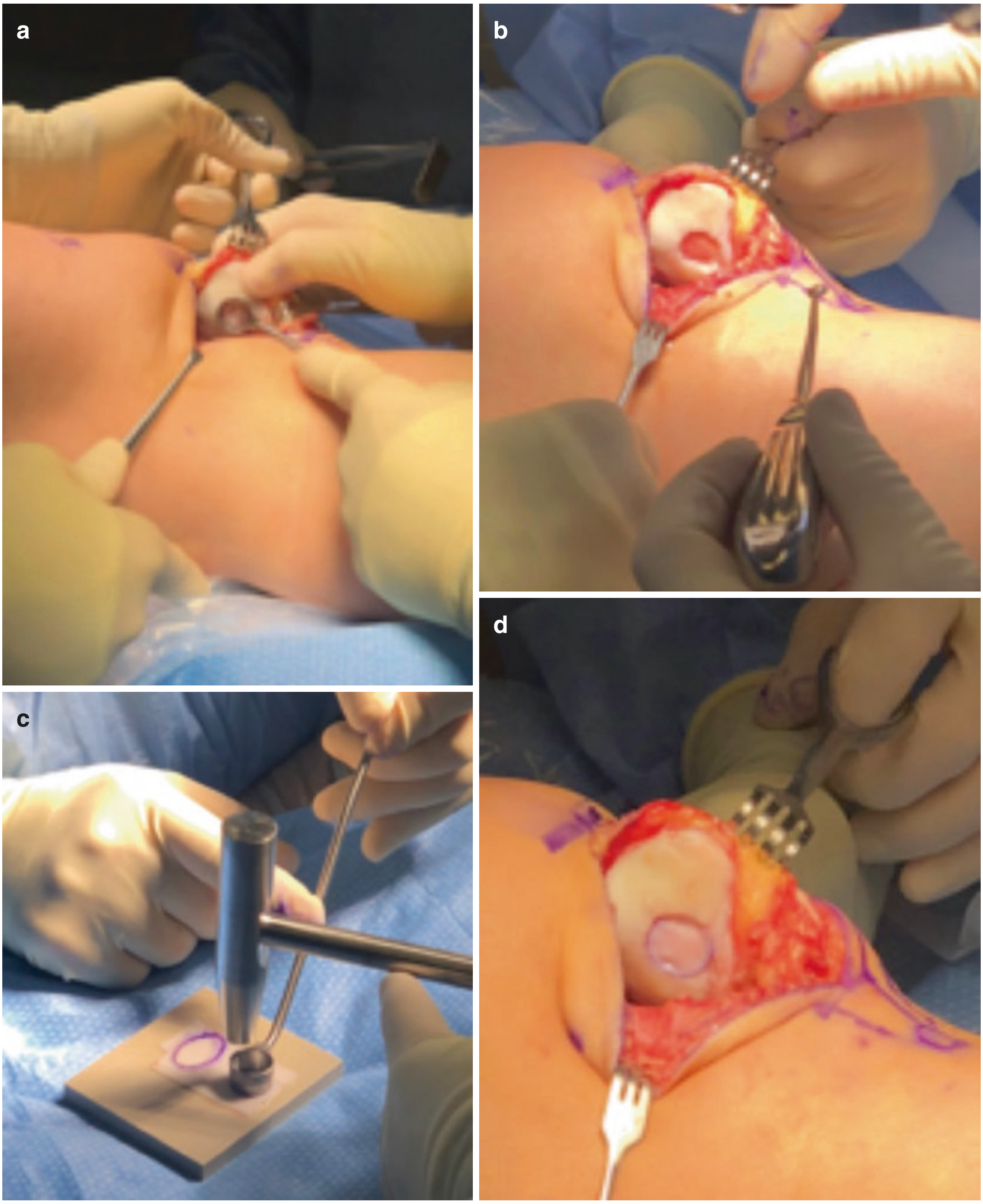


Fig. 29.3 MACI procedure to the patella. (**a**) Sizing of the patellar defect. (**b**) Patellar defect after debridement and preparation. (**c**) Cutting the autologous chondrocyte matrix to size to match the patellar defect. (**d**) Implantation of the matrix onto the patellar defect. (**e**) Sealing the matrix on the defect with fibrin glue

Fig. 29.3 (continued)

matrix for at least 4–6 weeks until the time of surgical implantation.

Results following ACI have achieved good rates of RTS, although with mixed results in high-performing athletes. A number of prospective studies have demonstrated that 33–96% of athletes RTS, with 60–80% returning to preinjury level of play [42].

In terms of patient's expectations for RTS, Niemeyer et al. found that of patients scheduled to undergo ACI, 70% expected they would RTS pain-free and 20% expected they would not have any restrictions returning to sports. Niemeyer et al. also found that 73.1% of patients were able to RTS, although the duration of exercise and number of sessions per week significantly decreased after surgery [43, 44]. In another study, neither location nor size of defect appeared to affect rate of RTS because only 31% of patients were able to maintain their previous level of competition, and 0.8% of patients were able to return to elite sports [45]. Mithöfer et al. found that in competitive football and soccer players undergoing ACI, over 80% RTS which was maintained at 5 years [46, 47].

While Krych et al. reported the highest RTS rates after ACI compared with other cartilage procedures, this population also had the smallest lesion and the youngest age compared to the other treatment groups; age has been shown to be an independent indicator of return to sport [40]. Higher level of competition, lack of previous procedures, and shorter duration between symptom onset and treatment have been documented in various studies to correlate to a higher RTS [41, 46, 47].

While one of the main drawbacks of using MACI in athletes has been the prolonged recovery process, Della Villa et al. found greater clinical outcomes as well as a faster recovery and RTS in 10.2 months, thus showing that a beneficial role for intensive rehabilitation in allowing for a faster return to level of competition. The level of improvement was also sustained at 5 years [26]. Mithöfer et al. found that the average RTS following ACI ranged from 18 to 25 months [46]. While this may be longer than that of a microfracture or OCA, the functional declines starting 24 months postoperatively have not been seen with ACI as with other procedures [42]. Long-term outcomes for patients undergoing MACI have been documented by Zaffagnini et al. who prospectively analyzed competitive athletes who underwent MACI with 10-year follow-up. Postoperatively, 64.5% of patients were able to return to a competitive level, with 58.1% returning to preinjury level of sport. Interestingly, this study reported 84% of patients without previous surgery returned to prior level of sport, while only 33% of patients with a previous surgery returned to the prior level of sport. Factors linked with a lower rate of RTS included high BMI, generative etiology, and older age [48].

29.4 Osteochondral Autograft Transplantation

Similar to OCAs, OAT also restores the native architecture of the knee, but does so by using the patient's native bone-cartilage unit from a non-weight-bearing area of the knee to replace the bone-cartilage unit (Fig. 29.4). OAT is indicated

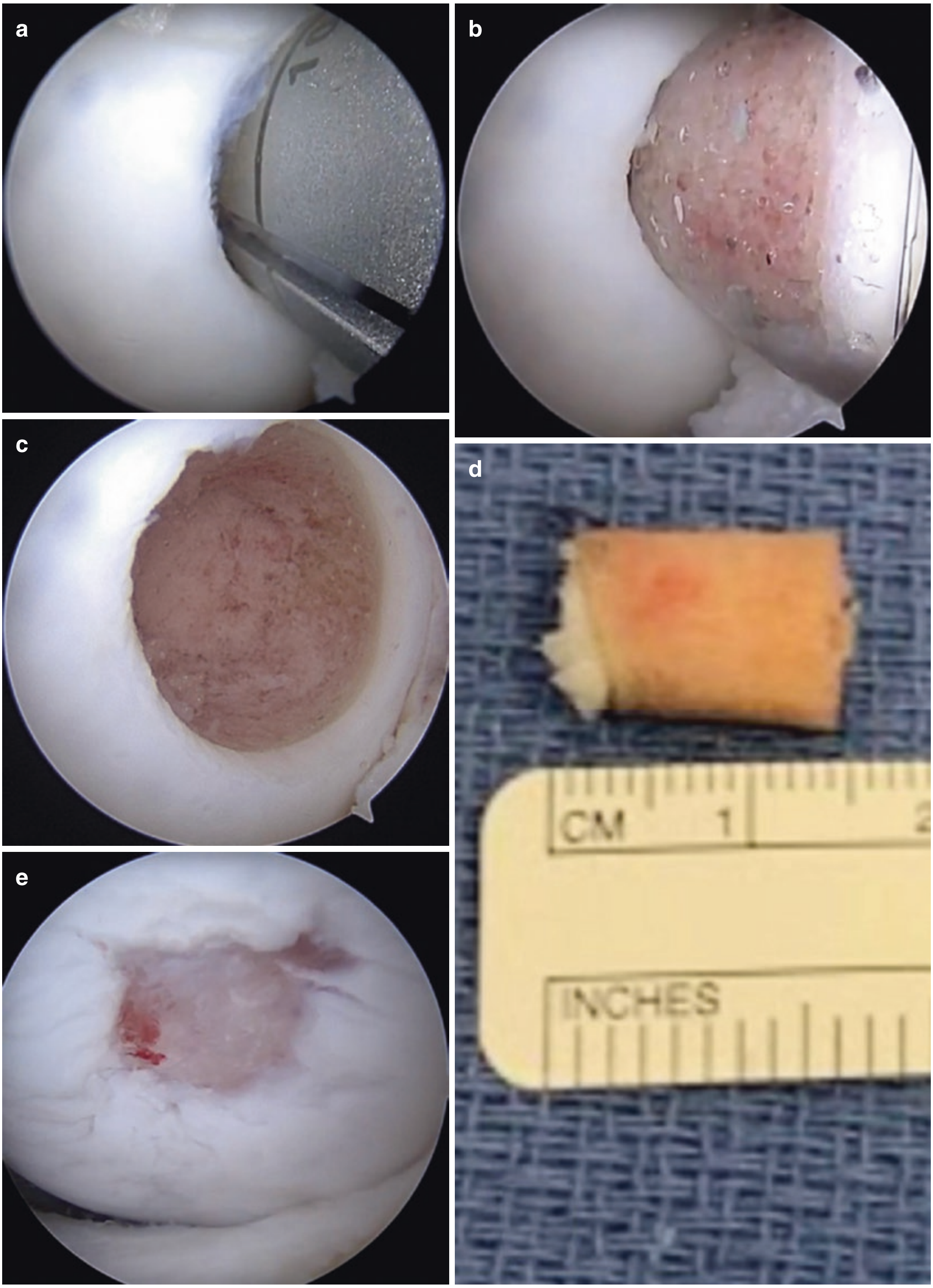


Fig. 29.4 Osteochondral autograft (OAT) harvest and implantation. (**a**) OAT harvest. (**b**) Retrieving the harvested autograft. (**c**) The osteochondral defect remaining in a non-weight-bearing portion of the knee after graft harvest. (**d**) Osteochondral autograft. (**e**) Focal osteochondral defect of the lateral femoral condyle (LFC). (**f**) Implantation of the osteochondral autograft in the LFC

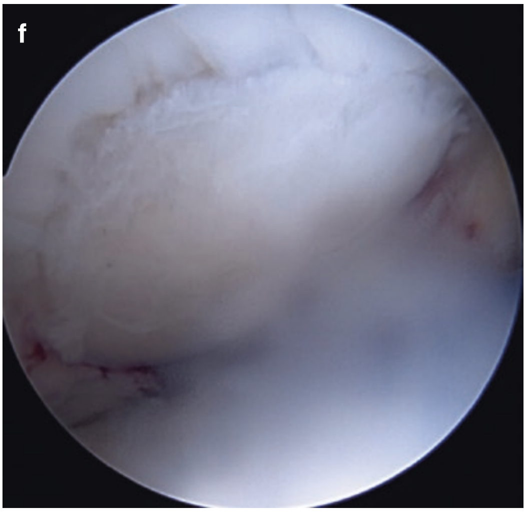


Fig. 29.4 (continued)

in patients with lesions <2 to 3 cm^2 with higher activity demands [49].

In a meta-analysis of 44 studies evaluating RTS with a minimum 2-year follow-up after microfracture, OAT, OCA, and ACI, Krych et al. found that the overall RTS for patients undergoing any procedure was 76%. The rate for RTS was highest for the patients undergoing OAT, with 93% RTS [40].

Minzlaff et al. evaluated 30 patients for a mean of 6.9 years with focal osteochondral defects who underwent OAT with valgus high tibial osteotomy. Eighty percent of the lesions were due to osteochondritis dissecans and 20% were post-traumatic. Patients were allowed to RTS after radiographic healing of the osteotomy. The study found that 1 year preoperatively, 76.7% of patients were participating in sports on a regular basis, while none were at the time of surgery due to the injury. At final follow-up, 76.7% were able to RTS. There was no significant difference between the number of patients involved in athletics 1 year preoperatively and at final follow-up. Of those who returned, 33% reported never having pain during sports, 40% had occasional pain, and 26.7% had regular pain during sports. Similar to studies of other procedures, there was a negative correlation found between the number of previous surgeries and the postoperative Tegner score [50].

Gudas et al. reported 93% of patients RTS at their preinjury level after OAT at an average of 6.5 months [51]. In a 10-year follow-up study, the same authors reported improved Tegner activity scores compared to preoperative values. There was a decrease, however, in sport activity as compared to 2-year outcomes. This decrease was less in the OAT group than it was in the microfracture group. Of note, patients less than 25 years old at the time of surgery were more likely to maintain their preinjury level of play 10 years postoperatively [52]. OAT has continued to show high RTS rates in the appropriate patient population, suggesting that it is an optimal treatment option for young, athletic patients with small osteochondral defects.

29.5 Osteochondral Allograft Transplantation

If the integrity of the underlying subchondral bone is compromised, a restorative procedure must address both the articular surface and the underlying subchondral bone. OCAs are used to restore the native architecture of the knee and do so by using a donor bone-cartilage unit to replace the damaged host bone and articular cartilage (Fig. 29.4). The OCA is harvested from a size-matched donor femoral condyle, trochlea, or patella and is implanted into the patient's knee after removal of the damaged bone and cartilage (Fig. 29.5).

OCA is favorable for its ability to treat the subchondral bone and articular cartilage of large lesions in a single procedure [53]. OCA is most successful in young patients with focal lesions that have been symptomatic for less than 1 year [53]. Outcomes are also more successful in patients with neutral or corrected alignment [53]. A systematic review of OCA surgery by De Caro et al. found 89% graft survivorship at 5 years postoperative, as well as improvement in clinical scores and accelerated RTS [54]. Familiari et al. reported good functional outcomes after OCA, with a mean 5-year survival rate of 86.7% and survival rates of 78.7%, 72.8%, and 67.5% at 10, 15, and 20 years, respectively [55]. Survival rates

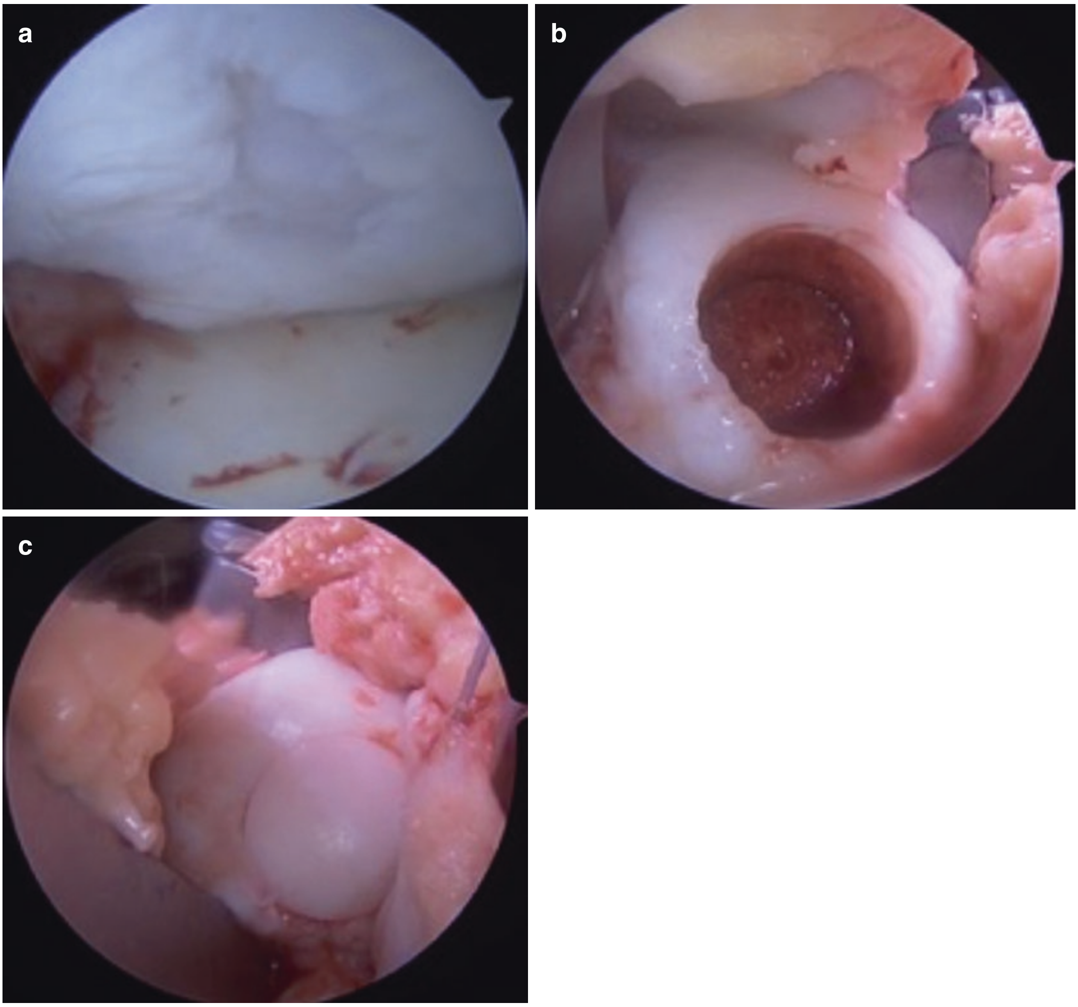


Fig. 29.5 Osteochondral allograft transplantation (OCA) of the left knee lateral femoral condyle (LFC). (**a**) LFC defect seen during arthroscopy. (**b**) Preparation of the LFC defect after reaming the bone (5–6 mm recommended to avoid immunogenic components of the bone). (**c**) Implantation of the size-matched OCA into the LFC defect

were similar in the patellofemoral joint as reported by Chahla et al. of 87.9%, 77.2%, and 55.8% at 5, 10, and 15 years, respectively [56]. Balazs et al. published a case series of 11 professional and collegiate basketball players undergoing OCA surgery. Of this cohort, 75% of NBA players and 83% of college players RTS at median times of 20 months and 8 months, respectively. Four patients underwent repeat arthroscopy, one of which was revision OCA. Three of these four players RTS, while the fourth underwent surgery after the patient was no longer eligible for play [57].

In a case series of 149 knees in 142 patients who participated in sport or recreational activity and underwent OCA, Nielsen et al. found that at a mean follow-up of 6 years, 75.2% had RTS or recreational activity. Postoperatively, patients were maintained on touchdown weight-bearing for 4–6 weeks, after which they progressed to full weight-bearing over the following month. Patients were allowed to participate in sport and recreational activities after 4–6 months if they demonstrated adequate functional rehabilitation of the affected limb. Of those who did not RTS, 88% reported they could still participate in regular exercise. About 25% of patients underwent additional surgery. The authors found that survivorship was 91% at 5 years and 89% at 10 years. They noted 14 failures, defined as revision, TKA, or unicompartmental arthroplasty. Of these failures, 13 did not RTS, while 1 was able to after transplant and converted to TKA after 11 years [58].

Krych et al. reported that at an average of 9.6 months following OCA, 88% of athletes returned to partial activity and 79% returned to full activity [40, 59]. It can be reasonably concluded from these studies that OCA is successful in returning patients to sport, most of whom return to their baseline level of play postoperatively.

29.6 Rehabilitation Protocol

The rehabilitation protocol for cartilage procedures in the authors' (BJC) practice is dependent on the compartment in which the procedure is done. Tables 29.1 and 29.2 detail the postoperative protocol after tibiofemoral compartment and patellofemoral cartilage restoration surgery, respectively. Concomitant meniscal allograft transplantation (MAT) affects the rehabilitation protocol. It is key to avoid tibial rotation for 8 weeks in order to protect the meniscus allograft. Weight-bearing is restricted to touch down only from 0 to 6 weeks and is advanced 25–100% from 6 to 8 weeks. The brace is locked in full extension at all times from 0 to 2 weeks, locked from 0 to 90° for 2–8 weeks, and discontinued at 8 weeks. All activities except for high-impact activities can be initiated at 6 months, while impact activities like running must be cleared by a physician, usually between 6 and 9 months.

29.7 Discussion

Symptomatic focal chondral defects in the knee can be a limiting factor for athletic play if they are not addressed in an appropriate fashion [14–20]. While all of the cartilage restoration procedures discussed have been shown to be successful in treating focal chondral defects when the proper patient and lesion indications

Table 29.2 Postoperative rehabilitation protocol for cartilage procedures of the patellofemoral compartment

Weight-bearing	
Immediate	Full weight-bearing
Brace	
Weeks 0–1	Locked in full extension at all times, off for CPM and exercise only
Weeks 1–4	Unlocked and worn during the daytime only, discontinue when quadriceps can control a single-leg raise without extension lag
Range of motion	
Weeks 0–2	Use CPM for 6 h/day, beginning at 0–30°
Weeks 2–4	Use CPM for 6 h/day, 0–60°
Weeks 4–6	Use CPM for 6 h/day, 0–90°
Weeks 6–8	Full ROM
Exercises	
Weeks 0 to 2	Quadriceps sets, single-leg raises, calf pumps, passive leg hangs to 45°
Weeks 2–6	Passive ROM and active ROM to tolerance, quadriceps, hamstring and glut sets, side-lying hip, and core exercises
Weeks 6–8	Advance exercises from weeks 2 to 6
Weeks 8–12	Gait training, wall sits, shuttle, mini-squats, toe raises, stationary bike, unilateral stance activities, and balance training
Week 12–6 months	Maximize core/glutes exercises, pelvic stability, eccentric hamstrings May advance to pool, elliptical, and bike as tolerated
6–12 months	Advance functional activities, return to sport-specific activity, and impact when cleared by physician after 8 months

CPM continuous passive motion, *ROM* range of motion are followed, treating athletes often involves a different definition of success postoperatively. Some athletes desire only pain relief and return to daily activities, but most are motivated to return to their preinjury level of play, while avoiding reinjury and the need for consequent treatment. Overall, cartilage procedures have high rates of RTS. Krych et al. found a return to sport rate of 76% across the discussed cartilage procedures, suggesting about three-fourth of patients who undergo these procedures are able to return to play [40]. Similarly, in a systematic review of cartilage procedures, Mithoefer et al. reported a 73% RTS rate [42]. Both studies, as well as a systematic review by Campbell et al., found the highest rates of RTS after OAT and the lowest after microfracture [60].

In contrast, Mithoefer et al. completed a systematic review of 20 studies evaluating RTS after articular cartilage repair in 1469 soccer players. They found 79% of athletes RTS with no significant difference between microfracture, ACI, OCA, and OAT. The time to RTS varied by procedure, with the shortest of 7 months after OCA and the longest of 17 months after ACI. Of these patients, 69% RTS at the preinjury level and 65% remained at preinjury level 3 years postoperatively. RTS was better for competitive athletes than for recreational athletes [61].

It is essential to appropriately manage patient's expectations regarding RTS after cartilage procedures. In order to do so, clinical studies must be completed to evaluate RTS outcomes after each procedure and identify patient demographics or lesion characteristics associated with positive outcomes. Makhni et al. found that only 14% of studies evaluating cartilage procedures analyzed reported outcomes related to RTS. Of those, only 11% of studies reported activity level after RTS and 6.6% of studies reported on time to RTS [62].

Factors that have been shown to correlate with increased RTS are younger age, shorter time between injury and surgery, no prior knee surgery, lower BMI, traumatic etiology, and smaller defects [48, 60]. It has been shown that those who had surgery within 1 year of surgery were 3–5 times more likely to RTS than those who did not have surgery as quickly, and a negative correlation was found between duration of symptoms and percentage of RTS [34, 37, 63].

29.8 Conclusion

RTS at a preinjury level of play after a cartilage procedure is possible in athletic patient populations with the appropriate treatment and indications. Physicians must approach the treatment algorithm with a patient's goals in mind in order to determine which treatment choice fits best to safely RTS, prevent reinjury, as well as to prevent the progression of the disease. It is also important to consider patient age, BMI, duration of symptoms, level of activity, future career goals, and previous knee interventions in order to identify the optimal treatment plan.

References

1. Montgomery SR, Foster BD, Ngo SS, et al. Trends in the surgical treatment of articular cartilage defects of the knee in the United States. Knee Surg Sport Traumatol Arthrosc. 2014;22(9):2070–5. https://doi.org/10.1007/s00167-013-2614-9.
2. McCormick F, Harris JD, Abrams GD, et al. Trends in the surgical treatment of articular cartilage lesions in the United States: an analysis of a large private-payer database over a period of 8 years. Arthrosc J Arthrosc Relat Surg. 2014;30(2):222–6. https://doi.org/10.1016/j.arthro.2013.11.001.
3. Widuchowski W, Widuchowski J, Trzaska T. Articular cartilage defects: study of 25,124 knee arthroscopies. Knee. 2007;14(3):177–82. https://doi.org/10.1016/j.knee.2007.02.001.
4. Curl WW, Krome J, Gordon ES, et al. Cartilage injuries: a review of 31,516 knee arthroscopies. Arthrosc J Arthrosc Relat Surg. 1997;13(4):456–60.. http://www.ncbi.nlm.nih.gov/pubmed/9276052
5. Provencher MT, Chahla J, Cinque ME, et al. Symptomatic focal knee chondral injuries in national football league combine players are associated with poorer performance and less volume of play. Arthrosc J Arthrosc Relat Surg. 2018;34(3):671–7. https://doi.org/10.1016/j.arthro.2017.08.300.
6. Southworth TM, Naveen NB, Nwachukwu BU, Cole BJ, Frank RM. Orthobiologics for focal articular cartilage defects. Clin Sports Med. 2019;38(1):109–22. https://doi.org/10.1016/j.csm.2018.09.001.
7. Cotter EJ, Wang KC, Yanke AB, Chubinskaya S. Bone marrow aspirate concentrate for cartilage

defects of the knee: from bench to bedside evidence. Cartilage. 2018;9(2):161–70. https://doi.org/10.1177/1947603517741169.
8. Roos H. Are there long-term sequelae from soccer? Clin Sports Med. 1998;17(4):819–31, viii. http://www.ncbi.nlm.nih.gov/pubmed/9922905
9. Elleuch MH, Guermazi M, Mezghanni M, et al. Knee osteoarthritis in 50 former top-level soccer players: a comparative study. Ann Readapt Med Phys. 2008;51(3):174–8. https://doi.org/10.1016/j.annrmp.2008.01.003.
10. Flanigan DC, Harris JD, Trinh TQ, Siston RA, Brophy RH. Prevalence of chondral defects in athletes' knees: a systematic review. Med Sci Sports Exerc. 2010;42(10):1795–801. https://doi.org/10.1249/MSS.0b013e3181d9eea0.
11. Walczak BE, McCulloch PC, Kang RW, Zelazny A, Tedeschi F, Cole BJ. Abnormal findings on knee magnetic resonance imaging in asymptomatic NBA players. J Knee Surg. 2008;21(1):27–33.. http://www.ncbi.nlm.nih.gov/pubmed/18300668
12. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. Am J Sport Med. 1995;23(6):694–701.
13. Piasecki DP, Spindler KP, Warren TA, Andrish JT, Parker RD. Intraarticular injuries associated with anterior cruciate ligament tear: findings at ligament reconstruction in high school and recreational athletes. An analysis of sex-based differences. Am J Sport Med. 2003;31(4):601–5. https://doi.org/10.1177/03635465030310042101.
14. Prakash D, Learmonth D. Natural progression of osteochondral defect in the femoral condyle. Knee. 2002;9(1):7–10. https://doi.org/10.1016/S0968-0160(01)00133-8.
15. Felson DT, Lawrence RC, Dieppe PA, et al. Osteoarthritis: new insights. Part 1: the disease and its risk factors. Ann Intern Med. 2000;133(8):635–46.. http://www.ncbi.nlm.nih.gov/pubmed/11033593
16. Kon E, Filardo G, Berruto M, et al. Articular cartilage treatment in high-level male soccer players: a prospective comparative study of arthroscopic second-generation autologous chondrocyte implantation versus microfracture. Am J Sports Med. 2011;39(12):2549–57. https://doi.org/10.1177/0363546511420688.
17. Buckwalter JA. Evaluating methods of restoring cartilaginous articular surfaces. Clin Orthop Relat Res. 1999;367(Suppl):S224–38.. http://www.ncbi.nlm.nih.gov/pubmed/10546649
18. Buckwalter J, Mankin H. Articular cartilage, II: degeneration and osteoarthrosis, repair, regeneration, and transplantation. J Bone Jt Surg Am. 1997;79:612–32.
19. Engström B, Forssblad M, Johansson C, Törnkvist H. Does a major knee injury definitely sideline an elite soccer player? Am J Sport Med. 1990;18(1):101–5. https://doi.org/10.1177/036354659001800118.
20. Drawer S, Fuller CW. Propensity for osteoarthritis and lower limb joint pain in retired professional soccer players. Br J Sports Med. 2001;35(6):402–8.. http://www.ncbi.nlm.nih.gov/pubmed/11726474
21. Homminga G, Bulstra S, Bouwmeester P, van der Linden A. Perichondral grafting for cartilage lesions of the knee. J Bone Joint Surg Br. 1990;72(6):1003–7.. http://www.ncbi.nlm.nih.gov/pubmed/2246280
22. Jensen LJ, Bach KL. Periosteal transplantation in the treatment of osteochondritis dissecans. Scand J Med Sci Sports. 2007;2(1):32–6. https://doi.org/10.1111/j.1600-0838.1992.tb00315.x.
23. Lawrence JS, Bremner JM, Bier F. Osteo-arthrosis. Prevalence in the population and relationship between symptoms and x-ray changes. Ann Rheum Dis. 1966;25(1):1–24.. http://www.ncbi.nlm.nih.gov/pubmed/5905334
24. Mithoefer K, Gill TJ, Cole BJ, Williams RJ, Mandelbaum BR. Clinical outcome and return to competition after microfracture in the athlete's knee: an evidence-based systematic review. Cartilage. 2010;1(2):113–20. https://doi.org/10.1177/1947603510366576.
25. Levy AS, Lohnes J, Sculley S, LeCroy M, Garrett W. Chondral delamination of the knee in soccer players. Am J Sport Med. 1996;24(5):634–9. https://doi.org/10.1177/036354659602400512.
26. Della Villa S, Kon E, Filardo G, et al. Does intensive rehabilitation permit early return to sport without compromising the clinical outcome after arthroscopic autologous chondrocyte implantation in highly competitive athletes? Am J Sports Med. 2010;38(1):68–77. https://doi.org/10.1177/0363546509348490.
27. Messner K, Maletius W. The long-term prognosis for severe damage to weight-bearing cartilage in the knee: a 14-year clinical and radiographic follow-up in 28 young athletes. Acta Orthop Scand. 1996;67(2):165–8. https://doi.org/10.3109/17453679608994664.
28. Cole BJ, Pascual-Garrido C, Grumet RC. Surgical management of articular cartilage defects in the knee. J Bone Joint Surg Am. 2009;91(7):1778–90. https://doi.org/10.1177/036354659602400302.
29. Scillia AJ, Aune KT, Andrachuk JS, et al. Return to play after chondroplasty of the knee in national football league athletes. Am J Sports Med. 2015;43(3):663–8. https://doi.org/10.1177/0363546514562752.
30. Redondo ML, Naveen NB, Liu JN, Tauro TM, Southworth TM, Cole BJ, et al. Sports Med Arthrosc Rev. 2018;26(4):e23–30. https://doi.org/10.1097/JSA.0000000000000226.
31. Fortier LA, Cole BJ, McIlwraith CW. Science and animal models of marrow stimulation for cartilage repair. J Knee Surg. 2012;25(1):3–8.. http://www.ncbi.nlm.nih.gov/pubmed/22624241
32. Bogunovic L, Wetters NG, Jain A, Cole BJ, Yanke AB. In vitro analysis of micronized cartilage stability in the knee: effect of fibrin level, defect size, and defect location. Arthroscopy. 2019;35(4):1212–8. https://doi.org/10.1016/j.arthro.2018.11.017.
33. Yanke AB, Cole BJ. Microfracture: dead or the future? Orthopedics. 2014;37(12):798–800. https://doi.org/10.3928/01477447-20141124-02.

34. Mithoefer K, Williams RJ, Warren RF, Wickiewicz TL, Marx RG. High-impact athletics after knee articular cartilage repair: a prospective evaluation of the microfracture technique. Am J Sports Med. 2006;34(9):1413–8. https://doi.org/10.1177/0363546506288240.
35. Gudas R, Stankevicius E, Monastyreckiene E, et al. Osteochondral autologous transplantation versus microfracture for the treatment of articular cartilage defects in the knee joint in athletes. Knee Surg Sport Traumatol Arthrosc. 2006;14(9):834–42.
36. Gill T. The treatment of articular cartilage defects using microfracture and debridement. Am J Knee Surg. 2000;13:33–40.
37. Mithoefer K, Williams RJ, Warren RF, et al. The microfracture technique for the treatment of articular cartilage lesions in the knee. A prospective cohort study. J Bone Joint Surg Am. 2005;87(9):1911–20. https://doi.org/10.2106/JBJS.D.02846.
38. Blevins FT, Steadman JR, Rodrigo JJ, Silliman J. Treatment of articular cartilage defects in athletes: an analysis of functional outcome and lesion appearance. Orthopedics. 1998;21(7):761–7.. http://www.ncbi.nlm.nih.gov/pubmed/9672913
39. Knutsen G, Engebretsen L, Ludvigsen TC, et al. Autologous chondrocyte implantation compared with microfracture in the knee. A randomized trial. J Bone Joint Surg Am. 2004;86-A(3):455–64.. http://www.ncbi.nlm.nih.gov/pubmed/14996869
40. Krych AJ, Pareek A, King AH, Johnson NR, Stuart MJ, Williams RJ. Return to sport after the surgical management of articular cartilage lesions in the knee: a meta-analysis. Knee Surg Sports Traumatol Arthrosc. 2017;25(10):3186–96. https://doi.org/10.1007/s00167-016-4262-3.
41. Minas T, Gomoll AH, Rosenberger R, Royce RO, Bryant T. Increased failure rate of autologous chondrocyte implantation after previous treatment with marrow stimulation techniques. Am J Sports Med. 2009;37(5):902–8. https://doi.org/10.1177/0363546508330137.
42. Mithoefer K, Hambly K, Della Villa S, Silvers H, Mandelbaum BR. Return to sports participation after articular cartilage repair in the knee: scientific evidence. Am J Sports Med. 2009;37(1_suppl):167S–76S. https://doi.org/10.1177/0363546509351650.
43. Niemeyer P, Porichis S, Salzmann G, Südkamp NP. What patients expect about autologous chondrocyte implantation (ACI) for treatment of cartilage defects at the knee joint. Cartilage. 2012;3(1):13–9. https://doi.org/10.1177/1947603511415840.
44. Niemeyer P, Andereya S, Angele P, et al. Autologous chondrocyte implantation (ACI) for cartilage defects of the knee: a guideline by the working group "Clinical Tissue Regeneration" of the German Society of Orthopaedic Surgery and Traumatology (DGOU). Knee. 2016;23:426–35. https://doi.org/10.1055/s-0032-1328207.
45. Pestka JM, Feucht MJ, Porichis S, Bode G, Südkamp NP, Niemeyer P. Return to sports activity and work after autologous chondrocyte implantation of the knee: which factors influence outcomes? Am J Sports Med. 2016;44(2):370–7. https://doi.org/10.1177/0363546515614578.
46. Mithoefer K, Peterson L, Saris DBF, Mandelbaum BR. Evolution and current role of autologous chondrocyte implantation for treatment of articular cartilage defects in the football (soccer) player. Cartilage. 2012;3(1 Suppl):31S–6S. https://doi.org/10.1177/1947603511406532.
47. Mithöfer K, Peterson L, Mandelbaum BR, Minas T. Articular cartilage repair in soccer players with autologous chondrocyte transplantation: functional outcome and return to competition. Am J Sports Med. 2005;33(11):1639–46. https://doi.org/10.1177/0363546505275647.
48. Zaffagnini S, Vannini F, Di Martino A, et al. Low rate of return to pre-injury sport level in athletes after cartilage surgery: a 10-year follow-up study. Knee Surg Sport Traumatol Arthrosc. 2018. https://doi.org/10.1007/s00167-018-5255-1.
49. Stone AV, Christian DR, Redondo ML, Yanke AB, Cole BJ. Osteochondral allograft transplantation and osteochondral autograft transfer. Oper Tech Sports Med. 2018;26(3):1–6.
50. Minzlaff P, Feucht MJ, Saier T, et al. Can young and active patients participate in sports after osteochondral autologous transfer combined with valgus high tibial osteotomy? Knee Surg Sport Traumatol Arthrosc. 2016;24(5):1594–600. https://doi.org/10.1007/s00167-014-3447-x.
51. Gudas R, Kalesinskas RJ, Kimtys V, et al. A prospective randomized clinical study of mosaic osteochondral autologous transplantation versus microfracture for the treatment of osteochondral defects in the knee joint in young athletes. Arthroscopy. 2005;21(9):1066–75. https://doi.org/10.1016/j.arthro.2005.06.018.
52. Gudas R, Gudaite A, Pocius A, et al. Ten-year follow-up of a prospective, randomized clinical study of mosaic osteochondral autologous transplantation versus microfracture for the treatment of osteochondral defects in the knee joint of athletes. Am J Sports Med. 2012;40(11):2499–508. https://doi.org/10.1177/0363546512458763.
53. Saltzman BM, Christian DR, Redondo ML, Cole BJ. Preserving the articulating surface of the knee. Amsterdam: Elsevier Inc.; 2019. https://doi.org/10.1016/B978-0-323-55140-3.00009-6.
54. De Caro F, Bisicchia S, Amendola A, Ding L. Large fresh osteochondral allografts of the knee: a systematic clinical and basic science review of the literature. Arthroscopy. 2015;31(4):757–65. https://doi.org/10.1016/j.arthro.2014.11.025.
55. Familiari F, Cinque ME, Chahla J, et al. Clinical outcomes and failure rates of osteochondral allograft transplantation in the knee: a systematic review. Am J Sports Med. 2018;46(14):3541–9. https://doi.org/10.1177/0363546517732531.
56. Chahla J, Sweet MC, Okoroha KR, et al. Osteochondral allograft transplantation in the

patellofemoral joint: a systematic review. Am J Sports Med. 2018:363546518814236. https://doi.org/10.1177/0363546518814236.
57. Balazs GC, Wang D, Burge AJ, Sinatro AL, Wong AC, Williams RJ. Return to play among elite basketball players after osteochondral allograft transplantation of full-thickness cartilage lesions. Orthop J Sports Med. 2018;6(7):1–7. https://doi.org/10.1177/2325967118786941.
58. Nielsen ES, McCauley JC, Pulido PA, Bugbee WD. Return to sport and recreational activity after osteochondral allograft transplantation in the knee. Am J Sports Med. 2017;45(7):1608–14. https://doi.org/10.1177/0363546517694857.
59. Krych AJ, Robertson CM, Williams RJ. Return to athletic activity after osteochondral allograft transplantation in the knee. Am J Sports Med. 2012;40(5):1053–9. https://doi.org/10.1177/0363546511435780.
60. Campbell AB, Pineda M, Harris JD, Flanigan DC. Return to sport after articular cartilage repair in athletes' knees: a systematic review. Arthroscopy. 2016;32(4):651–68.e1. https://doi.org/10.1016/j.arthro.2015.08.028.
61. Mithoefer K, Della VS. Return to sports after articular cartilage repair in the football (soccer) player. Cartilage. 2012;3(1 SUPPL):57S–62S. https://doi.org/10.1177/1947603511410419.
62. Makhni EC, Meyer MA, Saltzman BM, Cole BJ. Comprehensiveness of outcome reporting in studies of articular cartilage defects of the knee. Arthrosc J Arthrosc Relat Surg. 2016;32(10):2133–9. https://doi.org/10.1016/j.arthro.2016.04.009.
63. Mithoefer K, Williams RJ, Warren RF, et al. Chondral resurfacing of articular cartilage defects in the knee with the microfracture technique. surgical technique. J Bone Joint Surg Am. 2006;88(Suppl 1):294–304. https://doi.org/10.2106/JBJS.F.00292.

30 Return to Sport After Unicondylar, Patellofemoral, and Total Knee Arthroplasty

Frank R. Noyes, Sue Barber-Westin, and Timothy P. Heckmann

30.1 Introduction

This chapter summarizes return to sport (RTS) data from 52 studies involving 10,192 patients who underwent either unicompartmental tibiofemoral knee arthroplasty (UKA), patellofemoral arthroplasty (PFA), or total knee arthroplasty (TKA). The majority of these investigations focused on medial UKA (Fig. 30.1) and TKA (Table 30.1). Studies have shown that patients that participate in recreational activities over their lifetime may develop knee osteoarthritis (OA) and require UKA or TKA at a younger age than normally expected [1–3]. Partial and total knee replacement procedures are well-accepted treatment options for patients with end-stage OA and are frequently performed in former athletes, as well as individuals who wish to be physically active postoperatively. In 2013, Weinstein et al. [4] calculated that 655,800 TKA patients (in the USA) were 50–59 years old and 984,700 patients were 60–69 years old, indicating a large number of individuals that were expected to be active in fitness and recreational activities. Former athletes have high expectations after TKA of resuming recreational activities [5] which correlate strongly with postoperative patient satisfaction [6–8].

Several systematic reviews have been recently published regarding RTS after TKA [5, 9–14], but only a few have focused on UKA [5, 11, 15]. Withes et al. [14] reviewed 18 studies and found that RTS rates varied from 36% to 89% after TKA and from 75% to 100% after UKA. A trend toward return to low-impact activities was found after both operations. The authors noted a lack of evidence with regard to postoperative rehabilitation for individuals desiring to RTS. Our published systematic review regarding RTS after TKA noted high variability in return to recreational activities of 34–100% [9] and a complete absence of description of rehabilitation programs or factors that influenced the ability to RTS. Lorenze and Salsbery [16] also noted a lack of evidence for required physical therapy parameters after TKA in high-functioning patients desiring to RTS and proposed a program to improve strength, balance, flexibility, and aerobic conditioning.

Although many studies and reviews have appeared in the literature over the past 15 years describing results of PFA, the majority have

F. R. Noyes
Cincinnati Sports Medicine and Orthopaedic Center, The Noyes Knee Institute, Cincinnati, OH, USA

S. Barber-Westin (✉)
Noyes Knee Institute, Cincinnati, OH, USA
e-mail: sbwestin@csmref.org

T. P. Heckmann
Jewish Hospital Orthopaedic Sports Medicine and Rehabilitation, Cincinnati, OH, USA

Noyes Knee Institute, Cincinnati, OH, USA
e-mail: tpheckmann@mercy.com

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_30

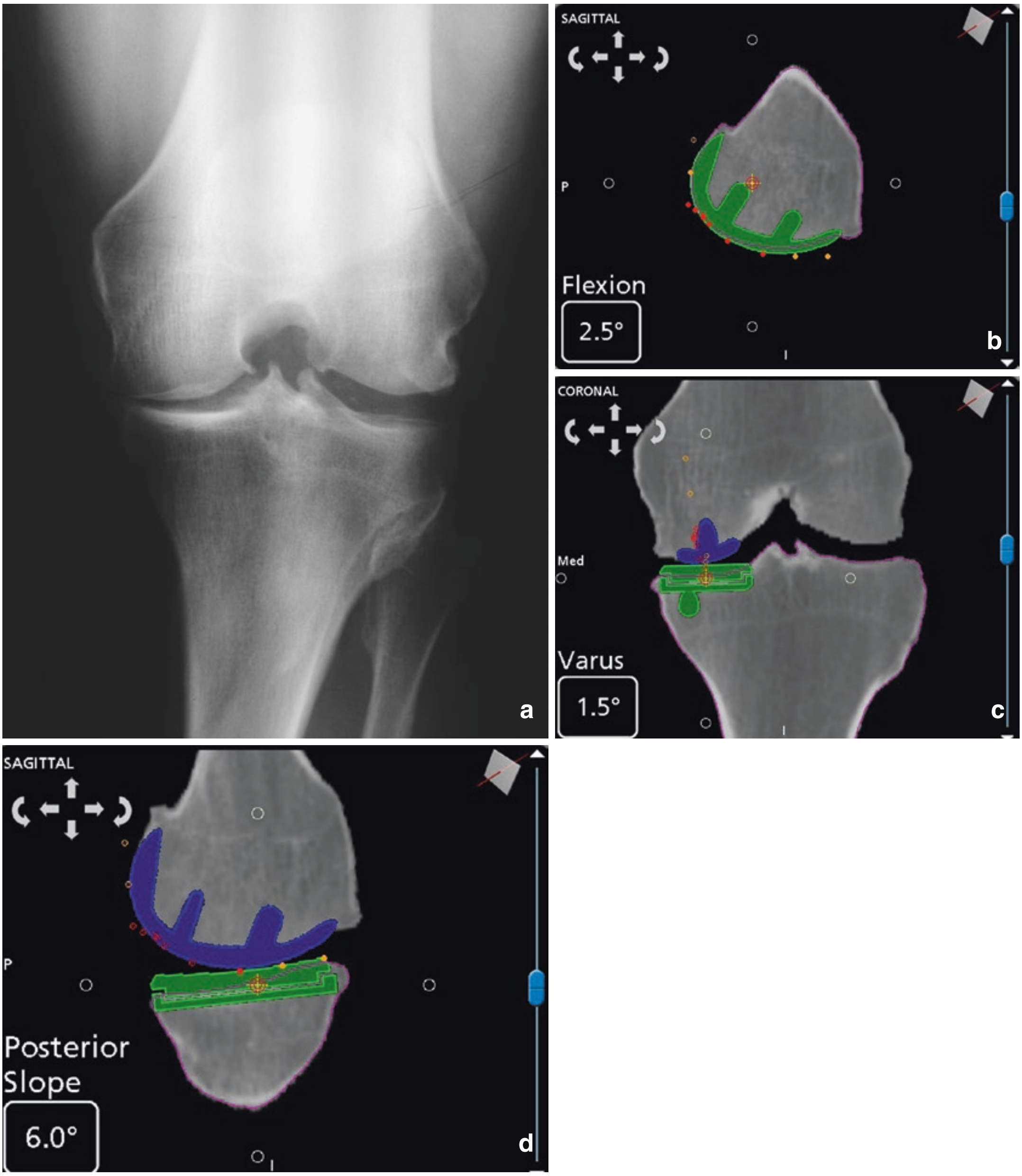


Fig. 30.1 Case of a 52-year-old man with advanced medial tibiofemoral compartment arthritis requiring a medial unicompartmental knee arthroplasty (UKA). (**a**) Preoperative standing 45° radiograph shows loss of the medial tibiofemoral compartmental space. (**b–d**) Preoperative planning for a MAKO medial UKA, with correction of the varus angulation to neutral. (**e**, **f**) Postoperative radiographs show excellent position of the implants. (Reprinted from Noyes and Barber-Westin [53])

focused on either short-term outcomes or survivorship [17–19]. Even fewer evidence-based studies are available regarding outcomes in terms of RTS after lateral UKA [20–23]. In this chapter, we explored all available literature regarding RTS after UKA, PFA, and TKA published from 2000 to 2018 to provide a comprehensive update.

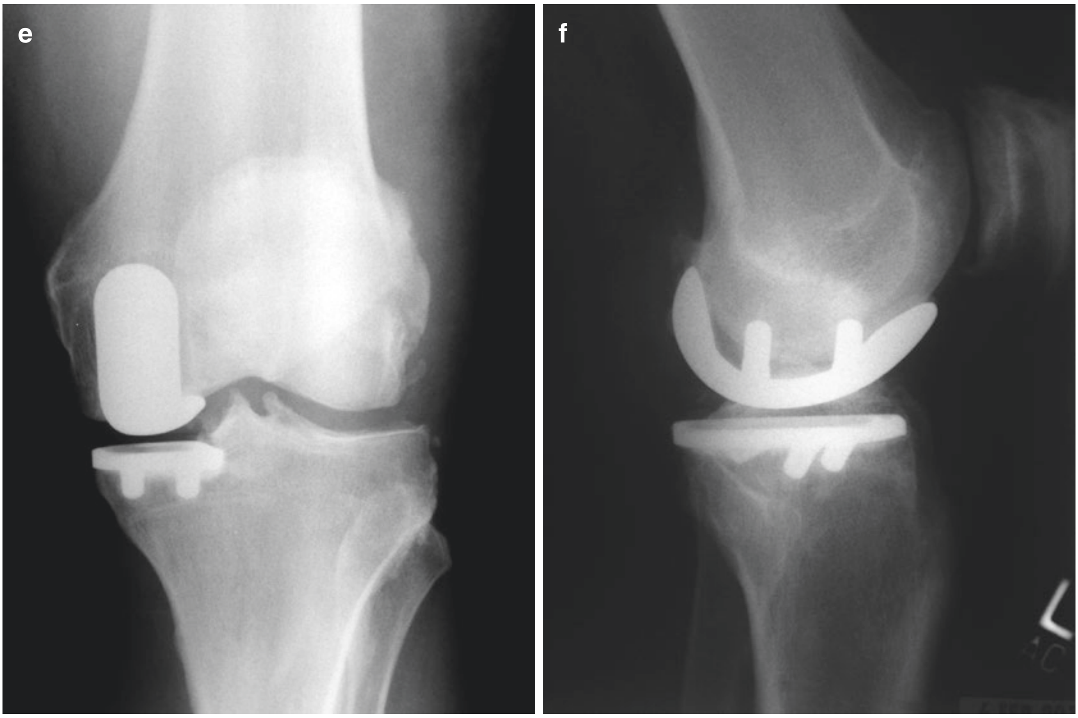


Fig. 30.1 (continued)

Table 30.1 Summary of studies reviewed

	All studies reviewed		RTS incidence rate		Sports scale ratings only		Implant failure data	
	Studies	Patients	Studies	Patients	Studies	Patients	Studies	Patients
Medial UKA	21	3628	12	1860	9	1768	15	3073
Lateral UKA	4	705	1	45	3	660	4	705
Patellofemoral arthroplasty	6	241	2	70	4	171	6	241
Total knee arthroplasty	21	5618	21	5618	0	0	9	1430

All data are numbers
RTS return to sports, *UKA* unicompartmental knee arthroplasty

30.2 RTS After Unicondylar Knee Arthroplasty

30.2.1 Medial UKA

We reviewed RTS data from 21 studies published from 2006 to 2018 involving 3628 patients who underwent medial UKA (Table 30.2) [24–44]. The mean age was approximately 61 (range, 32–94), and the mean follow-up was approximately 4 years (range, 3 months to 16 years). Sports activity levels were rated with the Tegner scale in eight studies, the University of California at Los Angeles (UCLA) scale in seven studies, the Grimby scale in one study, the High-Activity Arthroplasty Score in one study, and with three different scales in one study.

RTS incidence rates were given in 12 studies (Fig. 30.2) and ranged from 53% to 90%. The most common activities patients returned to were swimming, bicycling, walking, hiking, golfing, and bowling. The time required to RTS was provided in six studies and typically demonstrated that approximately 50–60% of the patients RTS by 3 months. Four studies [29, 34, 39, 42] determined if symptoms occurred during participation. Naal et al. [34] followed 83 patients a mean of 1.5 years postoperatively and reported that 88% RTS. However, 45%

Table 30.2 RTS after medial UKA

Study	Cohort			Implant	Sports scale	RTS data			Revision rate
	No. of patients	Mean age (range)	Mean follow-up year			RTS %[a], mean scores	Mean time RTS (months)	Comments, most common sports	
Hopper et al. [29]	34	61.3 (43–75)	1.8	Oxford	Authors' own	85% any sport; 73% same sport	3.6	27% decreased sports level, participation. 62% as a precaution, 13% due to pain in involved knee. Bowling, golf, swimming, bicycling	NP
Fisher et al. [27]	66	64.0 (49–81)	1.5	Oxford	UCLA	59% any sport; 54% same sport; preop 4.2, FU 6.5	NP	Swimming, golf, bowling, bicycling	3%
Jahnke et al. [31]	159	63.5 (36–86)	2.1	Oxford	Tegner, UCLA, Heidelberg Sports Activity Score	84% any sport; pre Tegner 4.1, FU 3.9; pre UCLA 6.1, FU 6.3	NP	Male gender, age <65 more active. Hiking, bicycling, swimming.	NP
Parratte et al. [40]	31	46 (41–49)	9.7	Miller-Galante	Authors' own	90% any sport, 60% same sport	NP	30% decreased sports level, participation	17%
Panzram et al. [39]	27	62.5 (49–76)	5.0	Oxford	UCLA, Tegner	89% any sport; pre UCLA 4.9, FU 6.1; pre Tegner 2.9, FU 3.4	63% by 3	15% pain in involved knee, 15% fear damage implant, 11% limited knee motion. Walking, bicycling, hiking	3%
Naal et al. [34]	83	65.5 (47–83)	1.5	Preservation	Authors' own	88% any sport	46% by 3, 23% 3–6, 31% >6	45% limited knee motion or not fit, 29% pain in involved knee, 26% pain in other joints, 10% felt anxious. Hiking, bicycling, swimming, walking	0%
Walton et al. [43]	150	71.5 (36–92)	1	Oxford	Grimby	86% any sport, 54% same sport; FU 3.9	3.1 63% by 3, 26% 3–6, 11% > 6	13% increased sports level, 19% decreased sports level. Walking, swimming, bicycling, hiking	NP
Walker et al. [42]	93	55 (36–60)	4.4	Oxford	UCLA	86% any sport; preop 3.3, FU 6.8	56% by 3, 21% 3–6, 23% > 6	17% pain in involved knee, 26% pain in other joints. Bicycling, walking, hiking	4%
Ali et al. [24]	1000	NP (61–17)	6.1	Oxford	Tegner	80% any sport	NP	Tegner score ≤4 in 88.5% and ≥5 in 11.5%	6%

Ho et al. [28]	36	60 (53–64)	3.8	NP	UCLA	72% any sport; pre 8.1, FU 7.4	2	Golf, bicycling, swimming, hiking	NP
Yim et al. [44]	50	60.3 (47–65)	3.7	Miller-Galante	Tegner	60% any sport; pre 3.2, FU 2.6	NP	None	6%
Pietschmann et al. [41]	131	65.3 (44–90)	4.2	Oxford III	UCLA	53% any sport; FU 6	NP	Low-impact sports	3%
Pandit et al. [37]	62	64 (45–82)	5.0	Oxford III	Tegner	Pre 1.9, FU 2.6	NP	None	0%
Pandit et al. [38]	512	65.1 (35–94)	3.4	Oxford III	Tegner	Pre 3, FU 3	NP	None	2%
Pandit et al. [36]	547	66 (32–88)	5.6	Oxford III	Tegner	Pre 2.3, FU 2.8	NP	None	3%
Krych et al. [32]	183	49.2 (NP)	5.6	Miller-Galante	Tegner	Pre 2.6, FU 4.5	NP	None	6%
Barker et al. [25]	44	63 (41–83)	2.0	Oxford	Tegner	Pre 2.2, FU 2.8	NP	None	NP
Liddle et al. [33]	132	64.8 (35–87)	5.0	Oxford	Tegner	Pre 2, FU 3	NP	None	NP
Biswas et al. [26]	75	49 (33–55)	4.0	Miller-Galante or Zimmer Uni knee	UCLA	Pre NP, FU 7.5	NP	None	4%
Naal et al. [35]	77	66 (46–84)	2.0	Preservation	UCLA	Pre NP, FU 6.5–7.3	NP	UCLA mean scores according to BMI: 7.3 BMI <25; 7.2 BMI 25–29.9; 6.5 BMI ≥30	4%
Hooper et al. [30]	136	63.6 (39–86)	5.0	Oxford	High-Activity Arthroplasty Score	Pre 4.3, FU 10.6	NP	None	1%

BMI body mass index, *FU* follow-up, *NP* not provided, *pre* preoperative, *RTS* return to sports, *UCLA* University of California Los Angeles, *UKA* unicompartmental knee arthroplasty

[a]RTS calculated as percentage of entire cohort

reported feeling limited in their knee motion or not physically fit, 29% had pain in their involved knee, and 10% felt unsafe or anxious during sports activities. Panzram et al. [39] reported 5-year outcomes in 27 patients, 89% of whom RTS. Problems included pain in 15%, fear of damaging the implant in 15%, and limited knee motion in 11%.

No study provided details of the rehabilitation program or criteria required for release to sports. Revision rates of the prostheses were <5% in 11 studies, 6% in 3 studies, and 17% in 1 study.

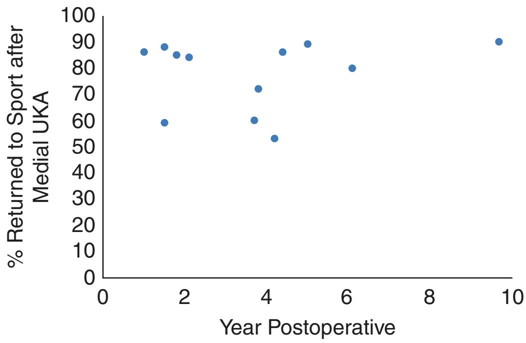


Fig. 30.2 The percent of patients who returned to any sport after medial unicompartmental knee arthroplasty

30.2.2 Lateral UKA

Few studies were available regarding RTS after lateral UKA. Only four investigations could be located at the time of writing, of which three provided only sports scale activity ratings (Table 30.3). The mean age ranged from 60 to 65 years and the mean follow-up ranged from 2.3 to 4.1 years. Walker et al. [45] reported in a study involving 45 patients that 96% RTS, most by 6 months postoperative. Factors that influenced UCLA activity levels were male gender and age <62 years. Mean Tegner scores provided in the four studies were low, ranging from 2.8 to 3.5. There was no mention of rehabilitation criteria required for release to activities. Revision rates ranged from 1% to 15%.

30.3 RTS After Patellofemoral Arthroplasty

We reviewed RTS data from six studies published from 2010 to 2018 involving 241 patients who underwent PFA (Table 30.4). The mean age ranged from 40 to 61, and the mean follow-up

Table 30.3 RTS after lateral UKA

Study	Cohort			Implant	Sports scale	RTS data			Revision rate (%)
	No. of patients	Mean age (range)	Mean follow-up year			RTS %[a], mean scores	Mean time RTS (months)	Comments, most common sports	
Walker et al. [45]	45	60.1 (36–81)	3.0	Oxford	Tegner, UCLA	96% any sport; Tegner pre 2.9, FU 3.5; UCLA pre 5.3, FU 6.7	56% by 3 78% by 6	Age <62 years, male gender more active Biking, walking, hiking. Two-thirds UCLA ≥7	4
Walker et al. [21]	327	65 (36–88)	3.1	Oxford	Tegner, UCLA	Tegner pre NP, FU 3.2; UCLA pre NP, FU 5.7	NP	None	15
Weston-Simons et al. [22]	265	64 (32–90)	4.1	Oxford	Tegner	Pre 2.2, FU 2.9	NP	None	8
Pandit et al. [64]	68	63 (42–85)	2.3	Oxford	Tegner	Pre 2.1, FU 2.8	NP	None	1

FU follow-up, *NP* not provided, *RTS* return to sports, *UCLA* University of California Los Angeles, *UKA* unicompartmental knee arthroplasty

[a]RTS calculated as percentage of entire cohort

Table 30.4 RTS after patellofemoral arthroplasty

Study	Cohort			Implant	Sports scale	RTS data			Revision rate (%)
	No. of patients	Mean age (range)	Mean follow-up year			RTS %[a], mean scores	Mean time RTS (months)	Comments, most common sports	
Noyes et al. [47]	31	40 (22–68)	4.0	Restoris, MAKOplasty	Cincinnati sports activity scale	87% any sport	NP	64% increased level, 13% same level. 10% playing with pain or limitations. Low-impact sports.	6
Shubin Stein et al. [46]	39	51.6 (32–73)	2.2	NP	Authors' own	72% any sport	NP	31% increased level, 22% same level, 19% decreased level. No effect of age, gender, type of arthritis (posttraumatic vs. osteoarthritis) on activity level at follow-up.	6
Dahm et al. [65]	59	56 (NP)	4.0	Avon	Tegner, UCLA	Tegner pre 2, FU 4; UCLA pre 3.4, FU 5.8	NP	None	3
Dahm et al. [66]	23	60 (39–81)	2.4	Avon	Tegner, UCLA	Tegner pre NP, FU 4.3; UCLA pre NP, FU 6.6	NP	Walking, swimming, bicycling, hiking	0
deDeugd et al. [67]	55	51 (36–81)	3.0	Avon	Tegner, UCLA	Tegner pre 1.9, FU 4.0; UCLA pre 3.0, FU 5.4	NP	None	1
Hofmann et al. [68]	34	61 (34–84)	2.5	Natural knee II	Tegner	Pre 2.6, FU 4.7	NP	None	12

FU follow-up, *NP* not provided, *RTS* return to sports, *UCLA* University of California Los Angeles
[a]RTS calculated as percentage of entire cohort

ranged from 2.2 to 4.0 years. Shubin Stein et al. [46] followed 39 patients a mean of 2.2 years postoperatively (range, 0.4–4.7 years) and reported that 72% RTS. The type of sports activities were not described and 6% required conversion to TKA. Four other investigations reported mean postoperative Tegner scores that ranged from 4.0 to 6.6. Conversion to TKA rates ranged from 0% to 12%. Postoperative rehabilitation was not described in any study.

We recently reported [47] mid-term outcomes (2–7 year postoperative) in 31 knees that underwent robotic PFA (MAKOplasty, Stryker) for degenerative arthritis or osteoarthritis secondary to either malalignment or trauma. A total of 96 prior operative procedures had been done, including patellofemoral realignment procedures in ten knees and articular cartilage restorative procedures in seven knees that failed to provide relief of symptoms. The operative procedure allowed precise reshaping of abnormal trochlear geometry (Fig. 30.3) with minimal bone resection and correction of medial patellofemoral ligament deficiency when required. A mean of 4 years postoperatively, 87% had returned to mostly light recreational activities (Table 30.5). Of those that returned, 74% increased their sports level, 15% participated in the same level, and 11% had symptoms with low-impact activities. There was no effect on the outcomes from concomitant patellofemoral realignment procedures or comorbidities. There were no symptomatic patellar subluxations or dislocations and only 6% required conversion to TKA.

30.4 RTS After Total Knee Arthroplasty

We reviewed 21 studies published from 2005 to 2018 in which RTS data was provided for 5618 TKA recipients (Table 30.6). This represents a small increase from our formal systematic review [9] that consisted of 19 studies (5169 knees). All of the 21 studies reported RTS incidence rates and details of athletic activity postoperatively. The mean patient age was approximately 67 years (actual range, 15–96), and the mean follow-up was approximately 5.3 years. The mean follow-up was <5 years in 13 studies, 5–9 years in five studies, and 10–21 years in three studies.

A mean of 72% of the patients RTS (range, 34–100%, Fig. 30.4); the calculated mean did not include three studies in which only patients who RTS were analyzed [48–50]. Nearly all studies reported return to low-impact activities such as walking for exercise, swimming, bicycling, hiking, bowling, and golf. An exception was the study by Mont et al. [49] that followed 21 men and 10 women 2–9.3 years postoperatively who all participated in high-impact activities such as tennis, jogging, and racquetball/squash. All but one patient had a successful outcome, with no reported problems with sports participation and no change in radiographic alignment of the prosthesis. One patient who jogged and played racquetball three times a week required a revision TKA.

The time to RTS after surgery was provided in seven studies. Chatterji et al. [51] followed 144 patients 1–2 years postoperatively and reported mean times to return to specific activities, which ranged from 6.9 weeks for water aerobics to 18.3 weeks for bowling. Jackson et al. [50] reported on 93 patients who returned to golf after TKA; 57% were playing at 6 months and 85% were playing within 12 months postoperatively. Knee-related symptoms were reported in 17%, but 94% reported enjoying the activity as much or even more after TKA. Only four other studies determined if symptoms or limitations occurred with sports activities. Hopper et al. [29] reported that 26% of 76 patients had pain and/or a feeling of instability during low-impact sports such as swimming, dancing, bowling, bicycling, and golf. Dahm et al. [52] followed 1206 patients a mean of 5.7 years postoperatively in whom 59%

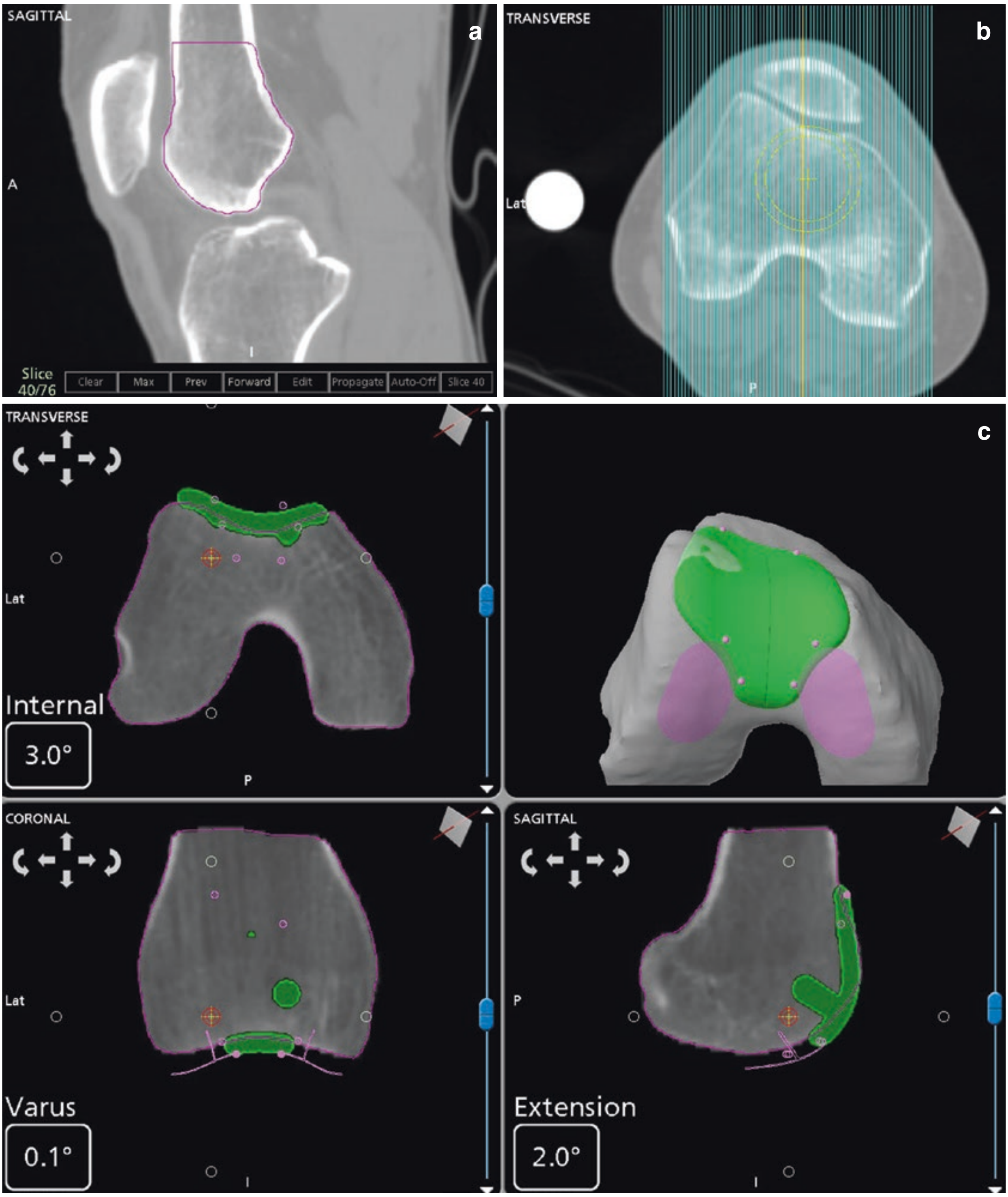


Fig. 30.3 Case of a 50-year-old woman with advanced patellofemoral arthritis and underlying trochlear dysplasia who presented with marked symptoms with daily activities. The preoperative coronal CT segment (**a**) and axial CT segment (**b**) images show trochlear dysplasia and hypoplasia of the medial aspect of the trochlea. (**c**) Intraoperative placement of the trochlear implant and resection required of the lateral trochlea for proper placement of the implant. Postoperative anterior (**d**) and lateral (**e**) radiographs demonstrate correct placement of the PFA. (Reprinted from Noyes and Barber-Westin [53], pp. 1036–1057)

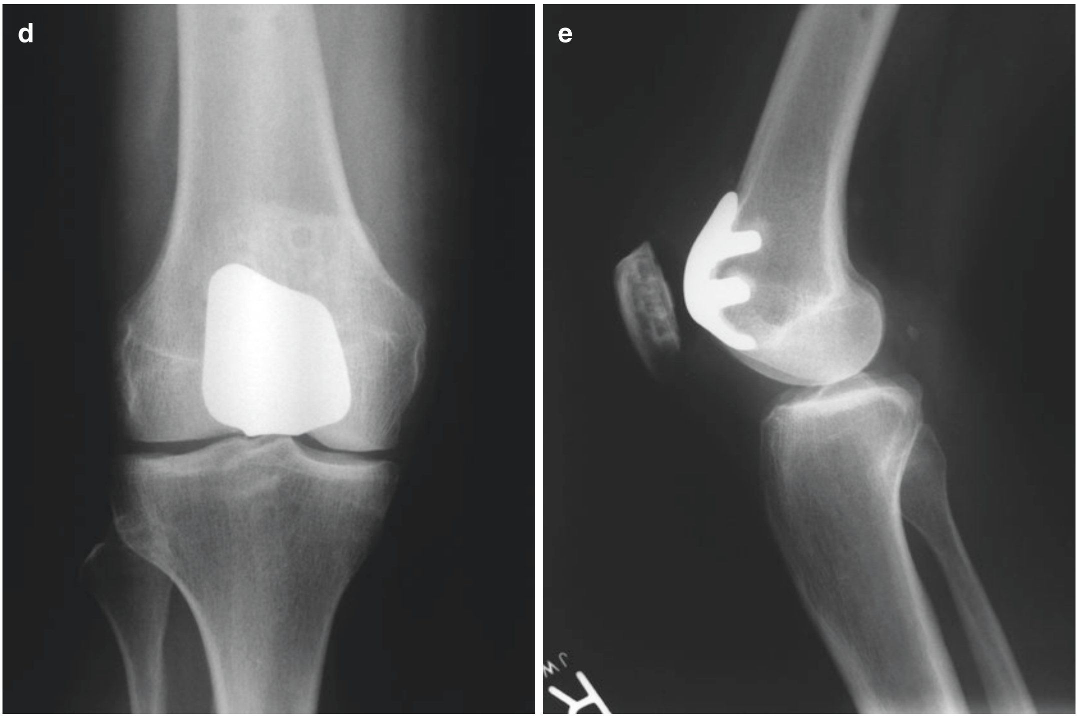


Fig. 30.3 (continued)

Table 30.5 Sports participation before and after PFA

Type of sport	Frequency	Preoperative (no)[a]	Follow-up (no)
Low-impact (cycling, swimming, aerobics)	1–3 day/month	0	5
	1–3 day/week	3	10
	4–7 day/week	3	11
			1
High-impact (jumping, pivoting, cutting)	1–3 day/week	1	
Not participating in any sports		24	4
Change in sports activities at follow-up			
Increased, no knee problems			20
Same, no knee problems			4
Playing with knee symptoms			3
Did not return because of knee condition			3
Did not return non-knee-related reasons			1

From Noyes et al. [47]
[a]All were participating with symptoms and functional limitations

RTS. Factors associated with higher UCLA scores were male gender, age <70 years, BMI <30, and unilateral TKA. Chatterji et al. [51] reported that there was no effect of age or gender on postoperative activity level.

Failure rates requiring revision TKA were reported in nine studies and ranged from 0% to 2%. No study provided details of the rehabilitation program or criteria required for release to sports.

Table 30.6 RTS after total knee arthroplasty

Study	Cohort			Implant	Sports scale	RTS data			Revision rate
	No. of patients	Mean age (range)	Mean follow-up year			RTS %*, mean scores	Mean time RTS (months)	Comments, most common sports	
Mont et al. [48]	114	40 (41–86)	7.0	Duracon	Authors' own	(only included patients that RTS)	NP	High-activity group (>1 activity 7 days/ week), walking, swimming, weight machines. Low-activity group walking, bicycling. High-activity participated mean 11×/week, low-activity mean 4×/ week	0%
Mont et al. [49]	33	66 (44–81)	3.7	Duracon	Authors' own	(only included patients that returned to high-impact sports)	NP	Tennis, high-impact aerobics, jogging, racquetball, squash	1%
Jackson et al. [50]	93	66 (44–79)	8.7	P.F.C. Sigma	UCLA	(only included patients that returned to golf) UCLA pre NP, FU 8.3	13% ≤ 3, 44% 4–6, 20% 7–9, 8% 10–12, 15% > 12	60% same level, 21% increased, 19% decreased. 17% playing with symptoms. 94% enjoyed golf as much or more after surgery	Excluded failures
Bauman et al. [69]	184	68.9 (41–88)	3.0	NP	UCLA	~92% any sport; pre NP, FU 6	NP	UCLA: 3 in 7.6%, 4 in 7.1%, 5 in 9.2%, 6 in 23.4%, 7 in 29.3%, 8 in 23.4%	0%
Meding et al. [70]	62	63.8 (18–82)	21.1	Posterior cruciate condylar or anatomic graduated component	UCLA	100% any sport; pre NP, FU 8.3	NP	UCLA: 5 in 5%, 6 in 11%, 7 in 15%, 8 in 33%, 9 in 21%, 10 in 15%	0%
Mayr et al. [71]	81	71.8 (60–80)	6.4	LCS	Authors' own	97% any sport	NP	None	1%
Walton et al. [43]	120	71.5 (29–95)	1.0	Variety	Grimby	87% any sport; pre NP, FU 2.8	3.8	30% same level, 14% increased, 43% decreased. Walking, swimming, bowling, fitness training	NP
Hepperger et al. [72]	200	72.2 (NP)	2.0	NexGen	Tegner	83% any sport; pre 3, FU 3	NP	Males more active than females. Hiking, skiing, bicycling, swimming	0%

(continued)

Table 30.6 (continued)

Study	Cohort			Implant	Sports scale	RTS data			Revision rate
	No. of patients	Mean age (range)	Mean follow-up year			RTS %∗, mean scores	Mean time RTS (months)	Comments, most common sports	
Argenson et al. [73]	412	71.6 (22–96)	3.0	LPS-Flex Mobile	UCLA	82% any sport; pre NP, FU 6.9	6	11% same level, 59% increased level, 11% decreased level. 14% playing with major limitation. Walking, hiking, swimming, exercising, bicycling, golf	1%
Chang et al. [74]	369	68.8 (50–83)	2.0	NP	UCLA	76% any sport; pre 4.5, FU 4.8	NP	UCLA: ≤ 3 in 11%, 4–6 in 80%, ≥ 7 in 9%. Walking, swimming, bicycling; increased frequency of moderate activity levels (4–6)	NP
Argenson et al. [75]	108	69 (37–85)	10.6	LPS-Flex Mobile	UCLA	75% any sport; pre NP, FU 6.4	6	18% decreased level, 6% playing with major limitation. Walking, hiking, swimming, bicycling, exercising, golf	2%
Chatterji et al. [51]	144	70.8 (NP)	1.5	Variety	Grimby	75% any sport	Water aerobics 1.6, walking 2, swimming 3, bowling 4.2	69% same level, 6% increased level. No effect of age or gender on activity level. Swimming, walking, bowling	NP
Wylde et al. [76]	866	69.6 (15–94)	2.0	NP	Authors' own	73% any sport	NP	Low-impact sports	NP
Vielgut et al. [77]	236	62.7 (NP)	14.9	LCS complete Mobile bearing	Tegner	71% any sport; pre 2.2, FU 3	NP	71% low-impact, 44% intermediate-impact sports. No effect of gender. Swimming, hiking, walking, fitness training, skating, badminton	2%
Ho [28]	40	59 (57–64)	4.2	NP	UCLA	70% any sport; pre 7.2, FU 6.1	4	Golf, bicycling, swimming, hiking	NP
Hopper et al. [29]	76	62.1 (35––75)	1.8	PFC	Authors' own	64% any sport	4.1	45% decreased level. 26% pain in involved knee, 26% instability during sports. Swimming, dancing, bowling, bicycling, golf	Excluded failures
Jones et al. [78]	83	66.5 (45–88)	1.0	Variety	Historical leisure activity questionnaire	64% any sport	NP	Walking, weight training, bicycling, dancing, swimming	NP

Dahm et al. [52]	1206	67 (20–91)	5.7	Press fit condylar or sigma	UCLA	59% any sport; pre NP, FU 7.1	NP	Age < 70, male gender, BMI < 30, unilateral TKA correlated with higher activity levels. Walking, bicycling, swimming, golf	Excluded failures
Parvizi et al. [79]	661	54 (19–60)	2.6	Variety	Authors' own	50% any sport	NP	33% pain, 41% stiffness, 54% difficulty with stairs	NP
Bonnin et al. [80]	141	66.4 (28–74)	3.7	Noetos or NexGen	Authors' own	35% any sport	NP	Higher motivation correlated with RTS. Hiking, bicycling, swimming	NP
Huch et al. [81]	389	66 (NP)	5.0	Variety	Authors' own	34% any sport	NP	Reduction or no return due to precaution 42%, pain elsewhere 29%. Swimming, bicycling, hiking	NP

*RTS calculated as percentage of entire cohort
BMI body mass index, *FU* follow-up, *NP* not provided, *RTS* return to sports, *UCLA* University of California Los Angeles

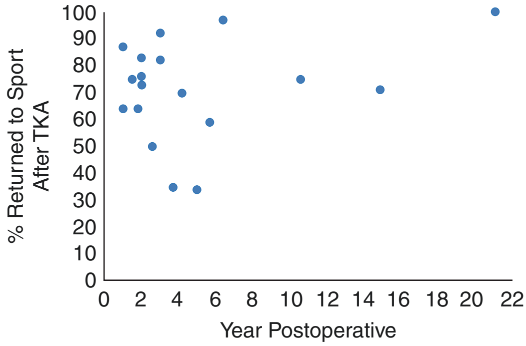


Fig. 30.4 The percent of patients who returned to any sport after TKA

30.5 Rehabilitation Principles for RTS After Partial or Total Knee Arthroplasty

We previously published our rehabilitation program for UKA [53] and PFA [54] procedures, which is outlined in Table 30.7. In addition, our program for TKA is shown in Table 30.8. We use robotic technology that allows precise positioning of the implants and ligament balancing required to achieve stability postoperatively (Fig. 30.5).

All patients begin immediate range of knee motion (ROM), patellar mobilization, quadri-

Table 30.7 Noyes Knee Institute rehabilitation for PFA and UKA

	Postoperative weeks					
	1–2	3–4	5–6	7–8	9–12	13–26
Range of motion minimum goals:						
0–110°	X					
0–135°		X				
Weight-bearing after UKA:						
50–75% body weight with assistive devices	X					
100% body weight, wean from assistive devices		X				
Weight-bearing after PFA:						
100% body weight with assistive devices	X					
100% body weight, wean from assistive devices		X				
Patella mobilization	X	X	X	X		
Modalities:						
Electrical muscle stimulation	X	X	X			
Pain/edema management (cryotherapy)	X	X	X	X	X	X
Stretching:						
Hamstring, gastrocnemius–soleus	X	X	X	X	X	X
Iliotibial band, quadriceps					X	X
Strengthening:						
Ankle pumps (plantar flexion with resistance band)	X	X				
Quadriceps isometrics, straight leg raises	X	X	X	X	X	X
Knee extension quadriceps, active/active-assisted	X					
Closed-chain: toe-raises, wall-sits, mini-squats		X	X	X	X	X
Knee flexion hamstring curls (0–90°)		X	X	X	X	X
Knee extension quadriceps (90–30°)		X	X	X	X	X
Hip abduction–adduction, multi-hip	X	X	X	X	X	X
Leg press (70–10°)		X	X	X	X	X
Upper body weight training			X	X	X	X
Core training			X	X	X	X
Balance/gait/proprioceptive training:						
Weight-shifting, balance board (two-legged), cup walking, tandem stance	X	X	X			
Mini-trampoline, balance board (single-legged; stable vs. unstable surface), single-leg stance				X	X	
Conditioning:						
Upper body conditioner	X	X	X	X	X	
Stationary bicycling (high seat, low resistance)		X	X	X	X	X

Table 30.7 (continued)

	Postoperative weeks					
	1–2	3–4	5–6	7–8	9–12	13–26
Aquatic program (water walking, depth at thigh or waist)			X	X	X	X
Swimming (straight leg kicking)				X	X	X
Stair-climbing machine (low resistance, low stroke)				X	X	X
Ski machine (short stride and level, low resistance)				X	X	X
Elliptical machine				X	X	X
Walking					X	X
Fitness center training:						
25 min strengthening, 25 min cardiovascular training, 10 min flexibility; 2–3×/week. Achieve AHA guidelines.[a] Watch for swelling, pain						X

BAPS Biomechanical Ankle Platform System, *BBS* Biodex Balance System
[a]American Heart Association guidelines: 30 min 5×/week moderate intensity (brisk walking, elevated heart rate); 20 min 3×/week vigorous intensity (exercise machine, bicycling)

Table 30.8 Noyes Knee Institute rehabilitation for TKA

	Postoperative weeks					
	1–2	3–4	5–6	7–8	9–12	13–26
Brace: Long-leg postoperative						
High-risk patients with concurrent patellar realignment or medial collateral ligament repair, or lack of quadriceps control, difficulty with balance/coordination	X	X				
Range of motion minimum goals:						
0–90°	X					
0–110°		X				
0–120°			X			
0–125°				X		
0–130°					X	
Weight-bearing:						
Toe touch to 50% body weight	X					
100% body weight, wean from assistive devices		X				
Patella mobilization	X	X	X	X		
Modalities:						
Electrical muscle stimulation	X	X	X			
Pain/edema management (cryotherapy)	X	X	X	X	X	X
Stretching:						
Hamstring, gastrocnemius–soleus, gluteal	X	X	X	X	X	X
Iliotibial band, quadriceps					X	X
Strengthening:						
Ankle pumps (plantar flexion with resistance band week 3)	X	X				
Quadriceps isometrics, straight leg raises	X	X	X	X	X	X
Knee extension quadriceps active-assisted	X					
Closed-chain: wall-sits		X	X	X	X	X
Closed-chain: toe/heel raises			X	X		
Closed-chain: lateral step-ups				X		
Knee flexion hamstring curls (0–90°)		X	X	X	X	X
Knee extension quadriceps (90–0°)		X	X	X	X	X
Hip abduction–adduction, multi-hip		X	X	X	X	X

(continued)

Table 30.8 (continued)

	Postoperative weeks					
	1–2	3–4	5–6	7–8	9–12	13–26
Leg press (80–10°)		X	X	X	X	X
Upper body weight training			X	X	X	X
Core training			X	X	X	X
Balance/gait/proprioceptive training:						
Weight-shifting, cup walking	X	X	X			
Balance board (two-legged), tandem stance		X	X			
Single-leg stance (ball catch week 7), band walking (forward, lateral)			X	X	X	
Band walking (diagonal, monster walk), star excursion balance reaching					X	
Conditioning:						
Upper body conditioner		X	X	X	X	
Stationary bicycling (high seat, low resistance)		X	X	X	X	X
Aquatic program (water walking, depth at thigh or waist)			X	X	X	X
Stair machine (low resistance, low stroke)				X	X	X
Ski machine (short stride, level, low resistance)				X	X	X
Elliptical machine				X	X	X
Swimming (kicking)					X	X
Walking					X	X
Fitness center training:						
25 min strengthening, 25 min cardiovascular training, 10 min flexibility; 2–3×/week. Achieve AHA guidelines.[a] Watch for swelling, pain						X

BAPS Biomechanical Ankle Platform System, *BBS* Biodex Balance System
[a]American Heart Association guidelines: 30 min 5×/week moderate intensity (brisk walking, elevated heart rate); 20 min 3×/week vigorous intensity (exercise machine, bicycling)

ceps strengthening, and balance training with partial weight-bearing allowed. A continuous passive motion machine is not required or routinely used [55, 56]. Patients perform passive and active ROM exercises in a seated position for 10 min a session, approximately six times per day. Patellar mobilization is performed before ROM exercises to restore a normal medial–lateral glide and prevent contracture of soft tissue patellar retinacular structures (Fig. 30.6). Full passive knee extension must be obtained immediately to avoid excessive scarring. If the patient has difficulty regaining at least 0° by the seventh postoperative day, he or she begins an overpressure program. The foot and ankle are propped on a towel or other device to elevate the hamstrings and gastrocnemius that allows the knee to drop into full extension (Fig. 30.7). This position is maintained for 10 min and repeated four to six times per day. A 10- to 20-pound weight may be added to the distal thigh and knee to provide overpressure to stretch the posterior capsule.

Knee flexion is gradually increased to 110° by the second postoperative week and 135° by the third to fourth postoperative week. Passive knee flexion exercises are performed initially in the traditional seated position, using the opposite lower extremity to provide overpressure. Other methods to assist in achieving flexion greater than 90° include chair rolling, wall slides, knee flexion devices (Fig. 30.8), and passive quadriceps stretching exercises.

Patients use a walker or crutches with full weight-bearing allowed as tolerated. Full weight-bearing without crutches is permitted when the patient demonstrates a normal gait pattern,

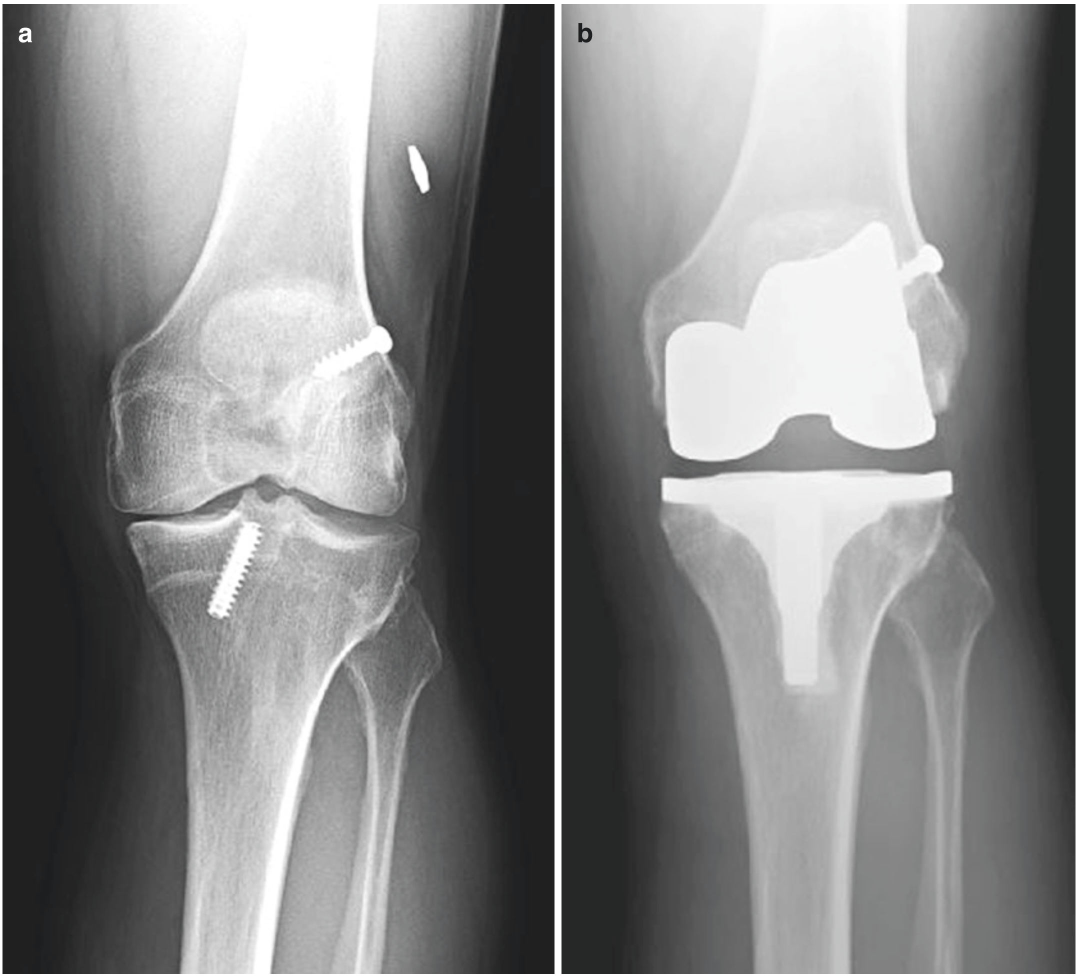


Fig. 30.5 (**a**) Preoperative and (**b**) postoperative radiographs of TKA

Fig. 30.6 Patellar mobilization may be performed postoperatively by (**a**) the therapist or (**b**) the patient

Fig. 30.7 Hanging weight exercise to restore knee extension

which is usually by the third to fourth postoperative week. Balance, proprioception, and strengthening exercises are gradually increased as supervised by the therapist through approximately the 12th postoperative week. At that time, the patient is encouraged to continue the strengthening and aerobic conditioning program as desired. If recreational sports are a goal, the criteria to begin training and resume these activities are described next.

30.5.1 Criteria for Return to Recreational Sports

As millions of younger patients undergo partial and TKA, the return to an active lifestyle is paramount. In 2007, the American Heart Association (AHA) and the American College of Sports Medicine published recommendations regarding the types of level of physical activity needed by healthy adults aged 18–65 years [57] and adults aged >65 years [58, 59]. The recommendations for aerobic activity were moderate-intensity activity for a minimum of 30 min for 5 days each week (150 min/week) or vigorous-intensity activity for at least 20 min for 3 days each week (60 min/week). Moderate-intensity activity produces increases in heart rate and breathing, whereas vigorous-intensity activity produces much larger increases. Muscle-strengthening exercises should be performed a minimum of 2 days a week and should include 8–10 resistance exercises.

After TKA, patients should gradually resume high-loading activities with the assistance of the therapy team, with caution required because too rapid a return may result in chronic joint swelling and muscle dysfunction that may require additional treatment measures. The therapist has the important position of monitoring active patients throughout the postoperative rehabilitation process who have greater demands on their knee from either an occupational or recreational activity standpoint. Studies have noted that many TKA patients do not achieve the AHA guidelines for physical activity [10] for a variety of reasons. We recommend the use of accelerometers because they provide data on all types of activity (light, moderate, and vigorous) and give feedback and motivation to patients. Reducing prolonged sitting and increasing daily step count are beneficial for even sedentary patients. These devices help active patients monitor daily activity, which may be shared with the medical team if problems with joint swelling and pain develop.

At our center, patients who desire to return to recreational sports after partial to total knee replacement such as golf, tennis, or skiing must pass a number of tests prior to the initiation of sports training (Table 30.9). There must be no

Table 30.9 Noyes Knee Institute criteria for return to recreational sports training after partial or total knee arthroplasty

Criteria/test	Goal
Pain	None, ≥6 Cincinnati knee rating pain scale
Swelling	None visible and ≥6 Cincinnati knee rating pain scale
Patellar mobility	Good
Gait	Symmetrical
Muscle strength quadriceps, hamstrings	Manual test: 5/5 Isometric max torque on Biodex: <30% deficit opposite side Isometric handheld dynamometer: <20% deficit opposite side
Muscle strength hip abductors	Manual test: 5/5 Isometric handheld dynamometer: <20% deficit opposite side
Single-leg squat test	No knee valgus, medial–lateral movement, or pelvic tilt
Stair climbing test	10 steps, up and down, can use rail: <13 s
6-min walk test[a]	Aged 60–69 years: male ≥521 m (0.32 mile), female ≥497 m (0.31 mile) Aged 70–79 years: male ≥478 m (0.29 mile), female ≥440 m (0.27 mile) Aged 80–89 years: male ≥356 m (0.22 mile), female ≥345 m (0.21 mile)
Star excursion balance test	Anterior, posterolateral, posteromedial directions (normalize each distance by patient's leg length): <10% deficit opposite side
Fitness training	Can be performed with no pain or swelling
PT/MD	Cleared for initiation of recreational sport training

[a]AHA guidelines: 30 min 5×/week moderate intensity (brisk walking, elevated heart rate); 20 min 3×/week vigorous intensity (exercise machine, bicycling)

Fig. 30.8 Knee flexion may be restored using (**a**, **b**) a rolling stool, (**c**) wall slides, and (**d**) a passive knee flexion commercial device

Fig. 30.9 Muscle strength testing with the Biodex

Fig. 30.10 Single-leg squat test

knee joint pain or swelling and gait must be symmetrical. Muscle strength testing is done with the equipment available for the quadriceps, hamstrings, and hip abductors (Fig. 30.9). Other useful tests include the single-leg squat test (Fig. 30.10) [60], stair-climbing test, 6-min walk test [61], and the Y-balance test (Fig. 30.11) [62, 63]. Upon satisfactory performance on these tests and clearance from the medical team, the patient may begin gradual sport-specific training (Table 30.10).

30.6 Conclusions and Comments

All available literature regarding UKA, PFA, and TKA published from 2000 to 2018 was reviewed to provide a comprehensive update regarding RTS incidence rates, time postoperatively RTS occurred, symptoms and limitations with sports participation, failure and revision rates, and rehabilitation criteria. Data from 21 studies after medial UKA showed an average RTS incidence rate of 78% (range, 53–90%), and data from 21 studies after TKA showed an average RTS incidence rate of 72% (range, 34–100%). There were too few studies of lateral UKA and PFA in which RTS information was provided to reach a conclusion. Nearly all studies reported return to low-impact activities such as walking for exercise, swimming, bicycling, hiking, bowling, and golf. Only 10 of the 52 studies determined if symptoms and/or limitations were experienced during sports or recreational activities. None of the studies provided rehabilitation exercises and criteria used to determine when RTS was feasible.

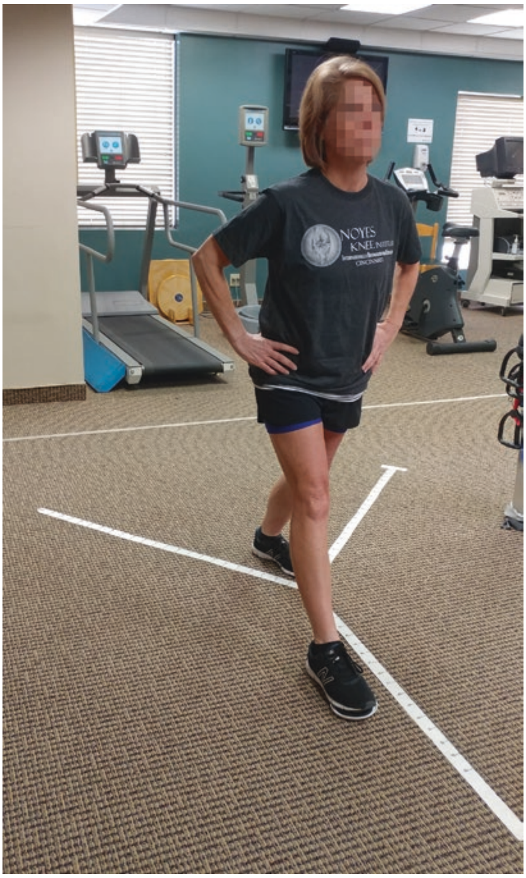


Fig. 30.11 Y-balance test

Table 30.10 Examples of recreational sport training progression

Sport	Progression
Golf	Start TheraBand simulation golf swing. Return to driving range, begin with short irons, progress to long irons and woods
Tennis	Begin ground strokes with ball machine or with pro 2–3×/week for 30 min; no running initially. Begin interval running half speed on the court when muscle strength >70% opposite side. Recommend return to doubles only
Skiing	Muscle strength must be ≥70% of opposite side to begin; increase balance training (half-foam rolls used to simulate side-to-side sway), perform wall sits >1 min

References

1. Elleuch MH, Guermazi M, Mezghanni M, Ghroubi S, Fki H, Mefteh S, Baklouti S, Sellami S. Knee osteoarthritis in 50 former top-level soccer players: a comparative study. Ann Readapt Med Phys. 2008;51(3):174–8. https://doi.org/10.1016/j.annrmp.2008.01.003.
2. Spector TD, Harris PA, Hart DJ, Cicuttini FM, Nandra D, Etherington J, Wolman RL, Doyle DV. Risk of osteoarthritis associated with long-term weight-bearing sports: a radiologic survey of the hips and knees in female ex-athletes and population controls. Arthritis Rheum. 1996;39(6):988–95.
3. Tveit M, Rosengren BE, Nilsson JA, Karlsson MK. Former male elite athletes have a higher prevalence of osteoarthritis and arthroplasty in the hip and knee than expected. Am J Sports Med. 2012;40(3):527–33. https://doi.org/10.1177/0363546511429278.
4. Weinstein AM, Rome BN, Reichmann WM, Collins JE, Burbine SA, Thornhill TS, Wright J, Katz JN, Losina E. Estimating the burden of total knee replacement in the United States. J Bone Joint Surg Am. 2013;95(5):385–92. https://doi.org/10.2106/JBJS.L.00206.
5. Jassim SS, Douglas SL, Haddad FS. Athletic activity after lower limb arthroplasty: a systematic review of current evidence. Bone Joint J. 2014;96-B(7):923–7. https://doi.org/10.1302/0301-620X.96B7.31585.
6. Scott CE, Bugler KE, Clement ND, MacDonald D, Howie CR, Biant LC. Patient expectations of arthroplasty of the hip and knee. J Bone Joint Surg. 2012;94(7):974–81. https://doi.org/10.1302/0301-620X.94B7.28219.
7. Noble PC, Conditt MA, Cook KF, Mathis KB. The John Insall award: patient expectations affect satisfaction with total knee arthroplasty. Clin Orthop Relat Res. 2006;452:35–43. https://doi.org/10.1097/01.blo.0000238825.63648.1e.
8. Husain A, Lee GC. Establishing realistic patient expectations following total knee arthroplasty. J Am Acad Orthop Surg. 2015;23(12):707–13. https://doi.org/10.5435/JAAOS-D-14-00049.
9. Barber-Westin SD, Noyes FR. Aerobic physical fitness and recreational sports participation after total knee arthroplasty. Sports Health. 2016;8(6):553–60. https://doi.org/10.1177/1941738116670090.
10. Naal FD, Impellizzeri FM. How active are patients undergoing total joint arthroplasty?: a systematic review. Clin Orthop Relat Res. 2010;468(7):1891–904. https://doi.org/10.1007/s11999-009-1135-9.
11. Papalia R, Del Buono A, Zampogna B, Maffulli N, Denaro V. Sport activity following joint arthroplasty:

a systematic review. Br Med Bull. 2012;101:81–103. https://doi.org/10.1093/bmb/ldr009.

12. Pozzi F, Snyder-Mackler L, Zeni J. Physical exercise after knee arthroplasty: a systematic review of controlled trials. Eur J Phys Rehabil Med. 2013;49(6):877–92.
13. Vogel LA, Carotenuto G, Basti JJ, Levine WN. Physical activity after total joint arthroplasty. Sports Health. 2011;3(5):441–50. https://doi.org/10.1177/1941738111415826.
14. Witjes S, Gouttebarge V, Kuijer PP, van Geenen RC, Poolman RW, Kerkhoffs GM. Return to sports and physical activity after total and unicondylar knee arthroplasty: a systematic review and meta-analysis. Sports Med (Auckland, NZ). 2016;46(2):269–92. https://doi.org/10.1007/s40279-015-0421-9.
15. Waldstein W, Kolbitsch P, Koller U, Boettner F, Windhager R. Sport and physical activity following unicompartmental knee arthroplasty: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2017;25(3):717–28. https://doi.org/10.1007/s00167-016-4167-1.
16. Lorenz DS, Salsbery MA. Return to high-level activity following knee replacement. Literature review and suggested program design. Topics Geiatric Rehab. 2013;29(1):46–54.
17. Lustig S. Patellofemoral arthroplasty. Orthop Traumatol Surg Res. 2014;100(1 Suppl):S35–43. https://doi.org/10.1016/j.otsr.2013.06.013.
18. van der List JP, Chawla H, Zuiderbaan HA, Pearle AD. Survivorship and functional outcomes of patellofemoral arthroplasty: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2017;25(8):2622–31. https://doi.org/10.1007/s00167-015-3878-z.
19. Walker T, Perkinson B, Mihalko WM. Patellofemoral arthroplasty: the other unicompartmental knee replacement. J Bone Joint Surg Am. 2012;94(18):1712–20. https://doi.org/10.2106/JBJS.L.00539.
20. Ollivier M, Abdel MP, Parratte S, Argenson JN. Lateral unicondylar knee arthroplasty (UKA): contemporary indications, surgical technique, and results. Int Orthop. 2014;38(2):449–55. https://doi.org/10.1007/s00264-013-2222-9.
21. Walker T, Zahn N, Bruckner T, Streit MR, Mohr G, Aldinger PR, Clarius M, Gotterbarm T. Mid-term results of lateral unicondylar mobile bearing knee arthroplasty: a multicentre study of 363 cases. Bone Joint J. 2018;100-b(1):42–9. https://doi.org/10.1302/0301-620x.100b1.Bjj-2017-0600.R1.
22. Weston-Simons JS, Pandit H, Kendrick BJ, Jenkins C, Barker K, Dodd CA, Murray DW. The mid-term outcomes of the Oxford domed lateral unicompartmental knee replacement. Bone Joint J. 2014;96-B(1):59–64. https://doi.org/10.1302/0301-620X.96B1.31630.
23. Zuiderbaan HA, Khamaisy S, Thein R, Nawabi DH, Pearle AD. Congruence and joint space width alterations of the medial compartment following lateral unicompartmental knee arthroplasty. Bone Joint J. 2015;97-B(1):50–5. https://doi.org/10.1302/0301-620X.97B1.33057.
24. Ali AM, Pandit H, Liddle AD, Jenkins C, Mellon S, Dodd CA, Murray DW. Does activity affect the outcome of the Oxford unicompartmental knee replacement? Knee. 2016;23(2):327–30. https://doi.org/10.1016/j.knee.2015.08.001.
25. Barker KL, Jenkins C, Pandit H, Murray D. Muscle power and function two years after unicompartmental knee replacement. Knee. 2012;19(4):360–4. https://doi.org/10.1016/j.knee.2011.05.006.
26. Biswas D, Van Thiel GS, Wetters NG, Pack BJ, Berger RA, Della Valle CJ. Medial unicompartmental knee arthroplasty in patients less than 55 years old: minimum of two years of follow-up. J Arthroplast. 2014;29(1):101–5. https://doi.org/10.1016/j.arth.2013.04.046.
27. Fisher N, Agarwal M, Reuben SF, Johnson DS, Turner PG. Sporting and physical activity following Oxford medial unicompartmental knee arthroplasty. Knee. 2006;13(4):296–300. https://doi.org/10.1016/j.knee.2006.03.004.
28. Ho JC, Stitzlein RN, Green CJ, Stoner T, Froimson MI. Return to sports activity following UKA and TKA. J Knee Surg. 2016;29(3):254–9. https://doi.org/10.1055/s-0035-1551835.
29. Hopper GP, Leach WJ. Participation in sporting activities following knee replacement: total versus unicompartmental. Knee Surg Sports Traumatol Arthrosc. 2008;16(10):973–9. https://doi.org/10.1007/s00167-008-0596-9.
30. Hooper N, Snell D, Hooper G, Maxwell R, Frampton C. The five-year radiological results of the uncemented Oxford medial compartment knee arthroplasty. Bone Joint J. 2015;97-b(10):1358–63. https://doi.org/10.1302/0301-620x.97b10.35668.
31. Jahnke A, Mende JK, Maier GS, Ahmed GA, Ishaque BA, Schmitt H, Rickert M, Clarius M, Seeger JB. Sports activities before and after medial unicompartmental knee arthroplasty using the new Heidelberg Sports Activity Score. Int Orthop. 2015;39(3):449–54. https://doi.org/10.1007/s00264-014-2524-6.
32. Krych AJ, Reardon P, Sousa P, Pareek A, Stuart M, Pagnano M. Unicompartmental knee arthroplasty provides higher activity and durability than valgus-producing proximal tibial osteotomy at 5 to 7 years. J Bone Joint surg Am. 2017;99(2):113–22. https://doi.org/10.2106/JBJS.15.01031.
33. Liddle AD, Pandit H, Jenkins C, Price AJ, Dodd CA, Gill HS, Murray DW. Preoperative pain location is a poor predictor of outcome after Oxford unicompartmental knee arthroplasty at 1 and 5 years. Knee Surg Sports Traumatol Arthrosc. 2013;21(11):2421–6. https://doi.org/10.1007/s00167-012-2211-3.
34. Naal FD, Fischer M, Preuss A, Goldhahn J, von Knoch F, Preiss S, Munzinger U, Drobny T. Return to sports and recreational activity after unicompartmental knee arthroplasty. Am J Sports Med. 2007;35(10):1688–95. https://doi.org/10.1177/0363546507303562.
35. Naal FD, Neuerburg C, Salzmann GM, Kriner M, von Knoch F, Preiss S, Drobny T, Munzinger U. Association of body mass index and clinical outcome 2 years after unicompartmental knee arthroplasty. Arch Orthop Trauma Surg. 2009;129(4):463–8. https://doi.org/10.1007/s00402-008-0633-7.

36. Pandit H, Jenkins C, Gill HS, Barker K, Dodd CA, Murray DW. Minimally invasive Oxford phase 3 unicompartmental knee replacement: results of 1000 cases. J Bone Joint Surg. 2011;93(2):198–204. https://doi.org/10.1302/0301-620X.93B2.25767.
37. Pandit H, Liddle AD, Kendrick BJ, Jenkins C, Price AJ, Gill HS, Dodd CA, Murray DW. Improved fixation in cementless unicompartmental knee replacement: five-year results of a randomized controlled trial. J Bone Joint Surg Am. 2013;95(15):1365–72. https://doi.org/10.2106/jbjs.L.01005.
38. Pandit HG, Campi S, Hamilton TW, Dada OD, Pollalis S, Jenkins C, Dodd CA, Murray DW. Five-year experience of cementless Oxford unicompartmental knee replacement. Knee Surg Sports Traumatol Arthrosc. 2015. https://doi.org/10.1007/s00167-015-3879-y.
39. Panzram B, Bertlich I, Reiner T, Walker T, Hagmann S, Gotterbarm T. Cementless unicompartmental knee replacement allows early return to normal activity. BMC Musculoskelet Disord. 2018;19(1):18. https://doi.org/10.1186/s12891-017-1883-8.
40. Parratte S, Argenson JN, Pearce O, Pauly V, Auquier P, Aubaniac JM. Medial unicompartmental knee replacement in the under-50s. J Bone Joint Surg. 2009;91(3):351–6. https://doi.org/10.1302/0301-620X.91B3.21588.
41. Pietschmann MF, Wohlleb L, Weber P, Schmidutz F, Ficklscherer A, Gulecyuz MF, Safi E, Niethammer TR, Jansson V, Muller PE. Sports activities after medial unicompartmental knee arthroplasty Oxford III-what can we expect? Int Orthop. 2013;37(1):31–7. https://doi.org/10.1007/s00264-012-1710-7.
42. Walker T, Streit J, Gotterbarm T, Bruckner T, Merle C, Streit MR. Sports, physical activity and patient-reported outcomes after medial unicompartmental knee arthroplasty in young patients. J Arthroplast. 2015;30(11):1911–6. https://doi.org/10.1016/j.arth.2015.05.031.
43. Walton NP, Jahromi I, Lewis PL, Dobson PJ, Angel KR, Campbell DG. Patient-perceived outcomes and return to sport and work: TKA versus mini-incision unicompartmental knee arthroplasty. J Knee Surg. 2006;19(2):112–6.
44. Yim JH, Song EK, Seo HY, Kim MS, Seon JK. Comparison of high tibial osteotomy and unicompartmental knee arthroplasty at a minimum follow-up of 3 years. J Arthroplast. 2013;28(2):243–7. https://doi.org/10.1016/j.arth.2012.06.011.
45. Walker T, Gotterbarm T, Bruckner T, Merle C, Streit MR. Return to sports, recreational activity and patient-reported outcomes after lateral unicompartmental knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2015;23(11):3281–7. https://doi.org/10.1007/s00167-014-3111-5.
46. Shubin Stein BE, Brady JM, Grawe B, Tuakli-Wosornu Y, Nguyen JT, Wolfe E, Voigt M, Mahony G, Strickland S. Return to activities after patellofemoral arthroplasty. Am J Orthop (Belle Mead NJ). 2017;46(6):E353–e357.
47. Noyes FR, Barber-Westin SD, Fleckenstein C, Riccobene J. Poster: Patellofemoral arthroplasty in younger patients: are recreational activities feasible? Paper presented at the AAOS 2018 Annual Meeting, New Orleans, Louisiana, March 6–10; 2018.
48. Mont MA, Marker DR, Seyler TM, Gordon N, Hungerford DS, Jones LC. Knee arthroplasties have similar results in high- and low-activity patients. Clin Orthop Relat Res. 2007;460:165–73. https://doi.org/10.1097/BLO.0b013e318042b5e7.
49. Mont MA, Marker DR, Seyler TM, Jones LC, Kolisek FR, Hungerford DS. High-impact sports after total knee arthroplasty. J Arthroplast. 2008;23(6 Suppl 1):80–4. https://doi.org/10.1016/j.arth.2008.04.018.
50. Jackson JD, Smith J, Shah JP, Wisniewski SJ, Dahm DL. Golf after total knee arthroplasty: do patients return to walking the course? Am J Sports Med. 2009;37(11):2201–4. https://doi.org/10.1177/0363546509339009.
51. Chatterji U, Ashworth MJ, Lewis PL, Dobson PJ. Effect of total knee arthroplasty on recreational and sporting activity. ANZ J Surg. 2005;75(6):405–8. https://doi.org/10.1111/j.1445-2197.2005.03400.x.
52. Dahm DL, Barnes SA, Harrington JR, Sayeed SA, Berry DJ. Patient-reported activity level after total knee arthroplasty. J Arthroplast. 2008;23(3):401–7. https://doi.org/10.1016/j.arth.2007.05.051.
53. Noyes FR, Barber-Westin SD. Unicompartmental knee replacement for varus or valgus malalignment. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 882–910. https://doi.org/10.1016/b978-0-323-32903-3.00030-5.
54. Noyes FR, Barber-Westin SD. Unicompartmental patellofemoral replacement. In: Noyes FR, Barber-Westin SD, editors. Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd ed. Philadelphia: Elsevier; 2017. p. 1036–57. https://doi.org/10.1016/b978-0-323-32903-3.00037-8.
55. Schulz M, Krohne B, Röder W, Sander K. Randomized, prospective, monocentric study to compare the outcome of continuous passive motion and controlled active motion after total knee arthroplasty. Technol Health Care. 2018;26(3):1–8.
56. McGrory BJ, Weber KL, Jevsevar DS, Sevarino K. Surgical management of osteoarthritis of the knee: evidence-based guideline. J Am Acad Orthop Surg. 2016;24(8):e87–93.
57. Haskell WL, Lee IM, Pate RR, Powell KE, Blair SN, Franklin BA, Macera CA, Heath GW, Thompson PD, Bauman A, American College of Sports M, American Heart A. Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. Circulation. 2007;116(9):1081–93. https://doi.org/10.1161/CIRCULATIONAHA.107.185649.
58. American College of Sports M, Chodzko-Zajko WJ, Proctor DN, Fiatarone Singh MA, Minson CT, Nigg CR, Salem GJ, Skinner JS. American College of Sports Medicine position stand. Exercise and physical activity for older adults. Med Sci Sports Exerc. 2009;41(7):1510–30. https://doi.org/10.1249/MSS.0b013e3181a0c95c.

59. Nelson ME, Rejeski WJ, Blair SN, Duncan PW, Judge JO, King AC, Macera CA, Castaneda-Sceppa C, American College of Sports M, American Heart A. Physical activity and public health in older adults: recommendation from the American College of Sports Medicine and the American Heart Association. Circulation. 2007;116(9):1094–105. https://doi.org/10.1161/CIRCULATIONAHA.107.185650.
60. Ireland ML, Bolgla LA, Noehren B. Gender differences in core strength and lower extremity function during static and dynamic single-leg squat tests. In: Noyes FR, Barber-Westin SD, editors. ACL injuries in the female athlete. Causes, impacts, and conditioning programs. 2nd ed. New York: Springer-Verlag Berlin Heidelberg; 2018. p. 239–57.
61. Ko V, Naylor JM, Harris IA, Crosbie J, Yeo AE. The six-minute walk test is an excellent predictor of functional ambulation after total knee arthroplasty. BMC Musculoskelet Disord. 2013;14:145. https://doi.org/10.1186/1471-2474-14-145.
62. Kinzey SJ, Armstrong CW. The reliability of the star-excursion test in assessing dynamic balance. J Orthop Sports Phys Ther. 1998;27(5):356–60.
63. Hegedus EJ, McDonough SM, Bleakley C, Baxter D, Cook CE. Clinician-friendly lower extremity physical performance tests in athletes: a systematic review of measurement properties and correlation with injury. Part 2--the tests for the hip, thigh, foot and ankle including the star excursion balance test. Br J Sports Med. 2015;49(10):649–56. https://doi.org/10.1136/bjsports-2014-094341.
64. Pandit H, Jenkins C, Beard DJ, Price AJ, Gill HS, Dodd CA, Murray DW. Mobile bearing dislocation in lateral unicompartmental knee replacement. Knee. 2010;17(6):392–7. https://doi.org/10.1016/j.knee.2009.10.007.
65. Dahm DL, Kalisvaart MM, Stuart MJ, Slettedahl SW. Patellofemoral arthroplasty: outcomes and factors associated with early progression of tibiofemoral arthritis. Knee Surg Sports Traumatol Arthrosc. 2014;22(10):2554–9. https://doi.org/10.1007/s00167-014-3202-3.
66. Dahm DL, Al-Rayashi W, Dajani K, Shah JP, Levy BA, Stuart MJ. Patellofemoral arthroplasty versus total knee arthroplasty in patients with isolated patellofemoral osteoarthritis. Am J Orthop (Belle Mead NJ). 2010;39(10):487–91.
67. deDeugd CM, Pareek A, Krych AJ, Cummings NM, Dahm DL. Outcomes of Patellofemoral Arthroplasty based on radiographic severity. J Arthroplast. 2017;32(4):1137–42. https://doi.org/10.1016/j.arth.2016.11.006.
68. Hofmann AA, McCandless JB, Shaeffer JF, Magee TH. Patellofemoral replacement: the third compartment. Bone Joint J. 2013;95-B(11 Suppl A):124–8. https://doi.org/10.1302/0301-620X.95B11.32985.
69. Bauman S, Williams D, Petruccelli D, Elliott W, de Beer J. Physical activity after total joint replacement: a cross-sectional survey. Clin J Sport Med. 2007;17(2):104–8. https://doi.org/10.1097/JSM.0b013e3180379b6a.
70. Meding JB, Meding LK, Ritter MA, Keating EM. Pain relief and functional improvement remain 20 years after knee arthroplasty. Clin Orthop Relat Res. 2012;470(1):144–9. https://doi.org/10.1007/s11999-011-2123-4.
71. Mayr HO, Reinhold M, Bernstein A, Suedkamp NP, Stoehr A. Sports activity following total knee arthroplasty in patients older than 60 years. J Arthroplast. 2015;30(1):46–9. https://doi.org/10.1016/j.arth.2014.08.021.
72. Hepperger C, Gfoller P, Abermann E, Hoser C, Ulmer H, Herbst E, Fink C. Sports activity is maintained or increased following total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2018;26(5):1515–23. https://doi.org/10.1007/s00167-017-4529-3.
73. Argenson JN, Parratte S, Ashour A, Komistek RD, Scuderi GR. Patient-reported outcome correlates with knee function after a single-design mobile-bearing TKA. Clin Orthop Relat Res. 2008;466(11):2669–76. https://doi.org/10.1007/s11999-008-0418-x.
74. Chang MJ, Kim SH, Kang YG, Chang CB, Kim TK. Activity levels and participation in physical activities by Korean patients following total knee arthroplasty. BMC Musculoskelet Disord. 2014;15:240. https://doi.org/10.1186/1471-2474-15-240.
75. Argenson JN, Parratte S, Ashour A, Saintmard B, Aubaniac JM. The outcome of rotating-platform total knee arthroplasty with cement at a minimum of ten years of follow-up. J Bone Joint Surg Am. 2012;94(7):638–44. https://doi.org/10.2106/JBJS.K.00263.
76. Wylde V, Blom A, Dieppe P, Hewlett S, Learmonth I. Return to sport after joint replacement. J Bone Joint Surg. 2008;90(7):920–3. https://doi.org/10.1302/0301-620X.90B7.20614.
77. Vielgut I, Leitner L, Kastner N, Radl R, Leithner A, Sadoghi P. Sports activity after low-contact-stress total knee arthroplasty - a long term follow-up study. Sci Rep. 2016;6:24630. https://doi.org/10.1038/srep24630.
78. Jones DL, Bhanegaonkar AJ, Billings AA, Kriska AM, Irrgang JJ, Crossett LS, Kwoh CK. Differences between actual and expected leisure activities after total knee arthroplasty for osteoarthritis. J Arthroplast. 2012;27(7):1289–96. https://doi.org/10.1016/j.arth.2011.10.030.
79. Parvizi J, Nunley RM, Berend KR, Lombardi AV Jr, Ruh EL, Clohisy JC, Hamilton WG, Della Valle CJ, Barrack RL. High level of residual symptoms in young patients after total knee arthroplasty. Clin Orthop Relat Res. 2014;472(1):133–7. https://doi.org/10.1007/s11999-013-3229-7.
80. Bonnin M, Laurent JR, Parratte S, Zadegan F, Badet R, Bissery A. Can patients really do sport after TKA? Knee Surg Sports Traumatol Arthrosc. 2010;18(7):853–62. https://doi.org/10.1007/s00167-009-1009-4.
81. Huch K, Muller KA, Sturmer T, Brenner H, Puhl W, Gunther KP. Sports activities 5 years after total knee or hip arthroplasty: the Ulm osteoarthritis study. Ann Rheum Dis. 2005;64(12):1715–20. https://doi.org/10.1136/ard.2004.033266.

Index

F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8

O

P