ACL Injuries in the Female Athlete

Causes, Impacts, and Conditioning Programs

Frank R. Noyes
Sue Barber-Westin
Editors

Second Edition

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Preface

This second edition of *ACL Injuries in the Female Athlete: Causes, Impacts, and Conditioning Programs* represents a significant update of all of the issues pertaining to the dilemma of the gender disparity in anterior cruciate ligament (ACL) injuries, first noted nearly 25 years ago. This textbook was designed to compile the many different approaches taken by clinicians and scientists regarding the female ACL injury problem. Our goal is to highlight the findings and current viewpoints of some of the individuals actively involved in this area of research. We are grateful to the guest authors, many of whom have published extensively on this topic, for their contributions to this effort.

In 1999, the first neuromuscular training program developed at Cincinnati Sports Medicine by Frank Noyes, M.D., and colleagues was published that reduced the incidence of ACL injuries in female high school athletes [1]. Researchers from around the world were soon involved in studying risk factors hypothesized to cause the ACL injury gender disparity, and similar training programs were developed in an attempt to reduce the incidence of noncontact ACL injuries. At the time of writing (July 2018), nearly 600 original research investigations and 100 reviews had been published that focused on ACL injuries in the female athlete. A recent Google search of “ACL Injury Prevention Training” revealed over one million hits, highlighting the popularity of this topic.

Having been at the forefront of this research topic, the editors find it refreshing to see the amount of intellectual energy and dollars that have been devoted to this area. In fact, multiple “ACL research retreats” (occurred in 1999, 2001, 2003, 2005, 2006, 2008, 2010, 2012, 2015) and consensus statements from organizations such as the International Olympic Committee [2] and the American Academy of Pediatrics [3] demonstrate the attention and emphasis the female athlete ACL injury dilemma has received throughout the world. Our nonprofit research foundation has certified over 2017 individuals across the USA and abroad to conduct neuromuscular ACL injury prevention programs in their communities.

As shown in this textbook, the majority of investigators have studied the causative factors producing the gender disparity in ACL injuries. Debate continues regarding the problem of deciphering the most relevant risk factors, and in fact, there remain questions on the exact mechanisms of this injury. Unfortunately, not everyone has jumped on the bandwagon regarding ACL injury prevention training. There remains a tremendous need and responsibility of medical health professionals to educate those involved with female athletes of the devastating consequences of ACL injuries and the need to prevent them. One potential solution to the “coach-not-interested” problem is to provide training programs that both enhance athletic performance and reduce the incidence of ACL injuries. This textbook describes programs designed for high-risk sports such as soccer and basketball that have accomplished both of these goals.

Another area still under investigation is the development of simple field tests to detect athletes with neuromuscular problems and imbalances that require correction. While laboratory work must continue using the most advanced three-dimensional motion, forceplate, electromyographic, and other equipment available, realistic and cost-effective tests are required. These could be incorporated into preseason physicals done by physicians or conducted by coaches as part of their athlete testing regimen. Several such field tests are detailed in this book.

It is our hope that someday ACL injury prevention training will truly be widespread and perhaps even a part of routine physical education classes at schools. Only through widespread use of prevention training will the female ACL injury problem be solved or at least significantly reduced. Until then, it remains the responsibility of those clinicians and scientists involved to continue their efforts to educate the general public and conduct research in the areas of risk factors, risk screening, and prevention programs.

In recent years, an even more pressing problem is the high rate of second ACL tears in athletes in the operative or opposite knee after an ACL reconstruction. Repeat ACL injuries have been reported to occur in as high as 30% of athletes [4, 5]. This is an enormous problem that needs research and development of postoperative programs that include neuromuscular training such as Sportsmetrics before an athlete returns to sports. In addition, the use of strict return to sport testing parameters, as detailed by the authors in this book, is required to objectively determine that neuromuscular, strength, and agility indices are in the normal to near normal range. It remains the responsibility of the surgeon and team of physical therapists and trainers treating athletes to adopt effective postoperative programs that combine all of the features of ACL preventive programs to lessen the risk of a serious repeat knee injury.

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Acronyms

ACL	Anterior cruciate ligament
ACL-RSI	ACL-Return to Sports After Injury scale
AE	Athlete exposure
JPS	Active joint position sense
AM	Anteromedial
AMI	Arthrogenic muscle inhibition
ANOVA	Analysis of variance
AP	Anteroposterior
BMD	Bone mineral density
BMI	Body mass index
B-PT-B	Bone-patellar tendon-bone
BSSTM	Behavioral and social science theories and models
BW	Body weight
CD	Compact disc
CEA	Center-edge angle
CKC	Closed kinetic chain
CNS	Central nervous system
cm	Centimeters
COF	Coefficient of friction
COM	Center of mass
COP	Center of pressure
COMP	Cartilage oligomeric matrix protein
CRI	Concussion Resolution Index
DEXA	Dual energy X-ray absorptiometry
DPSI	Dynamic postural stability index
EMG	Electromyographic or electromyography
EMS	Electrical muscle stimulation
ER	External rotation
FAI	Femoral acetabular impingement
FAST-FP	Functional Agility Short-Term Fatigue Protocol
FIFA	Federation Internationale de Football Association
FLE:EXT R	Absolute flexion force to absolute extension force ratio
FMS	Functional Movement System
FPPA	Frontal plane projection angle
FT	Fast twitch
FTA	Functional testing algorithm

GAG	Glycosaminoglycans
GMAX	Gluteus maximus
GMED	Gluteus medius
GRF	Ground reaction force
GRFV	Ground reaction force vector
rGRFV	Resultant ground reaction force vector
GTO	Golgi tendon organs
HBM	Health Belief Model
HHD	Hand-held dynamometry
H:Q	Hamstrings:quadriceps
IC	Initial contact
ICC	Intraclass correlation coefficients
IEMG	Integrated electromyography
IKDC	International Knee Documentations Committee
ImPACT	Immediate Post-Concussion Assessment and Cognitive Testing
IR	Internal rotation or incidence rates
IR/ER	Internal rotation/external rotation
ITB	Iliotibial band
JPS	Joint position sense
KIPP	Knee Injury Prevention Program
kg	Kilograms
KLIP	Knee Ligament Injury Prevention
KT and KT-2000	Knee arthrometer
LESS	Landing Error Scoring System
M	Meters
MAOT	Muscle activation onset time
min	Minutes
MMPs	Metalloproteinases
MMT	Manual muscle testing
mo	Month
MRI	Magnetic resonance imaging
MSFT	Multi-stage fitness test
ms	Milliseconds
MVC	Maximal voluntary contraction
MVE	Maximal voluntary excursions
NCAA	National Collegiate Athletic Association
NFL	National Football League
N	Newton
NA	Not available
Nm	Newton meters
NS	Not significant (statistically)
OA	Osteoarthritis
OKC	Open kinetic chain
OR	Odds ratio
PA	Posteroanterior
pEKAbM	Peak external knee abduction moment
PEP	Prevent Injury and Enhance Performance

PL	Posterolateral
PCL	Posterior cruciate ligament
pTIRM	Peak tibial internal rotation moment
PTP	Preventive training program
PTOA	Post-traumatic osteoarthritis
QH	Quadriceps-hamstrings
RE-AIM	Reach, Effectiveness, Adoption, Implementation, Maintenance
RE-AIM SSM	Reach, Effectiveness, Adoption, Implementation, Maintenance in a Sports Setting Matrix
RFD	Rate of force development
RM	Repetition max
RR	Relative risk
ROM	Range of motion
RTP	Return to play
RTS	Return to sport
s	Seconds
SEBT	Star Excursion Balance Test
SEPs	Somatosensory evoked potentials
SLO-FP	Slow Linear Oxidative Fatigue Protocol
SPECT	Single-photon emission computed tomography
ST	Slow twitch
StAART	Strategic Assessment of Risk and Risk Tolerance
STG	Semitendinosus-gracilis
TIMP	Tissue inhibitors of metalloproteinases
TDPM and TTDPM	Threshold for detection of passive motion
TLS	Total leg strength
TRIPP	Translating Research into Injury Prevention Practice
TSK	Tampa Scale for Kinesiophobia
TTDPM	Threshold to detect passive motion
US	United States
vGRF	Vertical ground reaction force
VMO	Vastus medialis oblique
VO_2max	Maximal oxygen uptake
VPAC	Volitional preemptive abdominal contraction
VSRP	Velocity spectrum rehabilitation protocols
WIPP	Warm-up for Injury Prevention and Performance
wk	Week
x	Times
yr	Year
3-D	3 Dimensional
2-D	2 Dimensional

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Part II Proposed Risk Factors of Noncontact ACL Injuries

Part III ACL Injury Prevention Programs

Part IV Reducing the Risk of Reinjury After ACL Reconstruction

Part V Future Directions

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Part I

The Impact of ACL Injuries: Short- and Long-Term Effects on the Knee Joint

1

The ACL: Anatomy, Biomechanics, Mechanisms of Injury, and the Gender Disparity

Frank R. Noyes and Sue Barber-Westin

Abstract

This chapter summarizes the current knowledge regarding ACL anatomy, biomechanics, common injury mechanisms, and the differences in ACL injury rates between male and female athletes. At least two-thirds of ACL tears occur during noncontact situations such as cutting, pivoting, accelerating, decelerating, and landing from a jump. Reduced knee flexion angles, increased hip flexion angles, valgus collapse at the knee, increased hip internal rotation, and increased internal or external tibial rotation are frequently reported at the time of or just prior to ACL injury. Female athletes are at greater risk for sustaining an ACL injury compared with male athletes participating in soccer, basketball, rugby, and handball. Research has shown that comprehensive training programs can effectively "reprogram" the neuromuscular system to avoid potentially dangerous body mechanics and positions.

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1.1 Introduction

Anterior cruciate ligament (ACL) tears are common knee ligament injuries that have serious short- and long-term consequences. Sanders et al. [1] reported the incidence of ACL tears according to age and gender in a 21-year study in the United States (US) (Fig. 1.1). The overall annual incidence of isolated ACL tears was 68.6 per 100,000 person-years. In women, the incidence was highest between the ages of 14 and 18 (incidence rate 227.6 per 100,000 person-years), whereas in males, ACL tears most commonly occurred between the ages of 19 and 25 (incidence rate 241.0 per 100,000 person-years). Data from the national patient register in Sweden (2002–2009) revealed the overall incidence of cruciate ligament injury to be 78 per 100,000 residents [2], with the highest incidence rates occurring in females aged 11–20 and in males aged 21–30. Beck et al. [3] reported data from 1994 to 2013 regarding the incidence of ACL tears in patients aged 6–18 years. The study population averaged 136,000 ± 15,000 subjects each year. The peak incidence of injury occurred during high school years, at age 16 for females (392 tears per 100,000 person-years; 0.392%) and age 17 for males (422 tears per 100,000 person-years; 0.422%). There was an annual increase in ACL tears of 2.3%.

Regardless of nationality, the majority of patients who sustain ACL injuries and undergo

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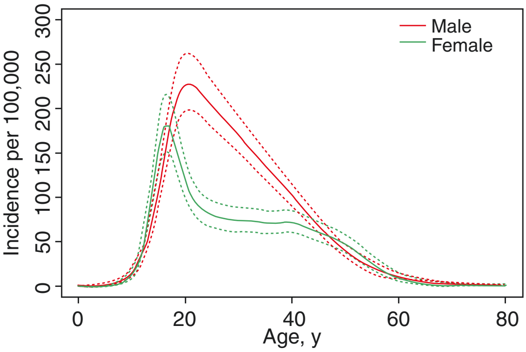

Fig. 1.1 Age-specific incidence of anterior cruciate ligament injuries in males and females (per 100,000 person-years) (Reprinted from Sanders TL, Maradit Kremers H, Bryan AJ, Larson DR, Dahm DL, Levy BA, Stuart MJ, Krych AJ (2016) Incidence of Anterior Cruciate Ligament Tears and Reconstruction: A 21-Year Population-Based Study. Am J Sports Med 44 (6):1502–1507)

reconstruction are athletes <25 years old who are frequently involved in high school, collegiate, or league sports [4–7]. At least two-thirds of ACL tears occur during noncontact situations while an athlete is cutting, pivoting, accelerating, decelerating, or landing from a jump [8, 9]. The term *noncontact* refers to no contact to the knee or leg in which the ACL is torn. The term *perturbation* refers to either a push or shove to the torso or upper extremity; this term may also refer to an athlete trying to avoid a collision with another athlete who is in close proximity. Perturbation has been noted to occur in the majority of ACL tears studied on videotape [8, 10, 11], as will be discussed. The costs of treatment of ACL tears are substantial; lifetime estimated costs per patient are 38,121 USD when treated with reconstruction and 88,538 USD when treated with rehabilitation. Athletes who suffer concomitant meniscus tears (that require resection) or other ligament tears are at increased risk for premature osteoarthritis [12–17]. As well, patients may suffer from deterioration of emotional health as a result of an ACL injury and the subsequent treatment required [18–21].

The initial reports of a higher incidence of noncontact ACL injuries in female athletes compared with male athletes participating in soccer and basketball first appeared in the medical literature in 1994–1995 [22, 23] and continue today [24]. Since then, researchers worldwide have spent considerable time and effort in attempting to understand why this disparity exists and if interventions such as neuromuscular retraining can lessen the difference in injury rates between genders.

Critical Points

- Overall annual incidence of isolated ACL tears was 68.6 per 100,000 person-years.
- ACL tears occur most commonly between the ages of 14 and 18 in women and between the ages of 19 and 25 in men.
- Majority of athletes involved are in high school, collegiate, or league sports.
- Two-thirds of ACL tears are noncontact.
- Gender disparity of ACL injury rates was first published in 1994.

1.2 Anatomy

1.2.1 Overview

Many authors have described the anatomy of the ACL [25–30]. The average length of the ACL is 32 mm (range, 22–41 mm) and its width in the midsubstance ranges from 7 to 17 mm [31, 32]. A recent study using open magnetic resonance imaging (MRI) reported significant differences in mean overall ACL lengths according to the angle of knee flexion [27]. The mean lengths obtained from 11 women and 9 men were 31.75 ± 2.5 mm in the hyperextended position (angle not provided), 32.5 ± 2.6 mm in the neutral position (0°), 33.5 ± 1.8 mm at 45° of flexion, and 35.6 ± 1.6 at 90° of flexion ($P < 0.0001$). This study did not conduct a gender comparison of ACL lengths.

The ACL originates on the medial aspect of the lateral femoral condyle (Fig. 1.2). Its origin, which may be oval or semicircular in appearance, is approximately 18 mm long and 10 mm wide and lies just behind a bony ridge (resident's ridge) that is anterior to the posterior

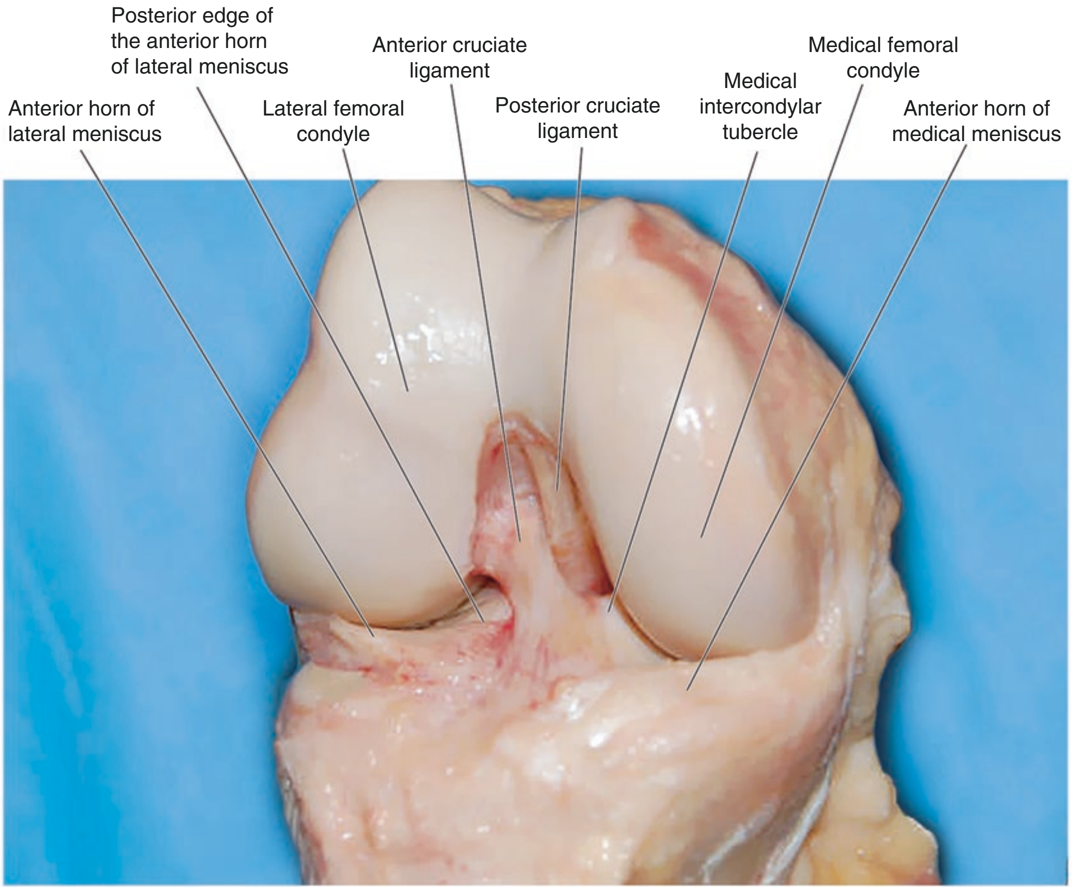

Fig. 1.2 Anterior view of the knee demonstrating the oblique orientation of the ACL originating on the medial aspect (side wall) of the lateral femoral condyle (Reprinted from Strickland J, Fester E, Noyes FR (2017) Lateral and posterior knee anatomy. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 23–35)

cartilage of the lateral femoral condyle. The insertion of the ACL, which is a roughly oval to triangular pattern, is located in the anterior intercondylar area of the tibia. The insertion fans out and resembles a "duck's foot" (Fig. 1.3) [33]. The anteroposterior dimension of the insertion is approximately 18 mm, and the mediolateral dimension is 10 mm. The anterior border of the ACL is approximately 22 mm from the anterior cortex of the tibia and 15 mm from the anterior edge of the articular surface. Its center is 15–18 mm anterior to the retro-eminence ridge (also termed the intercondylar eminence) (Fig. 1.4) [34, 35]. The medial and lateral tibial spines are referred to as the medial and lateral intercondylar tubercles [34]. The ACL insertion is just lateral to the tip of the medial intercondylar tubercle, with >50% inserting anterior to the posterior edge of the anterior horn of the lateral meniscus.

The ACL contains four types of mechanoreceptors, including Ruffini corpuscles, Pacinian corpuscles, Golgi-like tendon organs, and free nerve endings [36, 37]. Mechanoreceptors in the ACL are important for their role in knee proprioception and dynamic neuromuscular stability. In knees with ACL ruptures, the total number of mechanoreceptors decreases with the passage of time from injury to surgery regardless of age and gender [37].

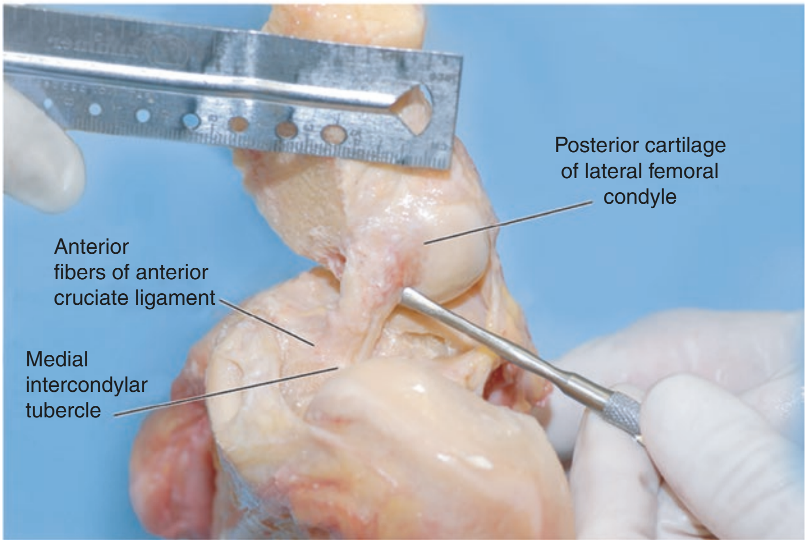

Fig. 1.3 Lateral view of the ACL. The anterior extension of the tibial insertion of the ACL is well visualized (Reprinted from Strickland J, Fester E, Noyes FR (2017) Lateral and posterior knee anatomy. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 23–35)

1.2.2 Division of ACL into Anteromedial and Posterolateral Bundles

Disagreement exists among researchers and surgeons regarding the division of the ACL into two distinct fiber bundles. While some investigators provide evidence of an anatomic and functional division, others argue that ACL fiber function is too complex to be artificially divided into two bundles. Amis et al. [31] and Colombet et al. [38] are among those who state that the anteromedial bundle (AMB) functions as the proximal half of the attachment that tightens with knee flexion. In contrast, the posterolateral bundle (PLB) is the distal half that tightens with knee extension. This occurs as the ACL femoral attachment changes from a vertical to a horizontal structure with knee motion. The problem is that this description of tightening and relaxation of the AMB and PLB represents that which occurs under no loading conditions in the laboratory. When substantial anterior tibial loading or the coupled motions of anterior translation and internal tibial rotation are experimentally induced, the majority of the ACL fibers are brought into a load-sharing configuration [39, 40].

We believe the classification of the ACL as a structure comprised of two fiber bundles represents a gross oversimplification not supported by biomechanical studies [29, 39–43]. The length-tension behavior of ACL fibers is primarily controlled by the femoral attachment (in reference to the center of femoral rotation), the combined motions applied, the resting length of the ACL fibers, and the tibial attachment locations. All ACL fibers anterior to the center lengthen during knee flexion, while the posterior fibers lengthen during knee extension. Under loading conditions, fibers in both the AMB and PLB contribute to resist tibial displacements. The function of the ACL fibers is determined by the anterior-to-posterior direction (with the knee at extension), as well as the proximal-to-distal femoral attachment.

In a recent study at our laboratory [44], the effect and interaction of the AMB and PLB of the ACL in resisting pivot-shift medial and lateral tibiofemoral compartment subluxations were studied. The robotic analysis showed that both bundles functioned in a synergistic manner in resisting subluxations in both the Lachman and pivot-shift tests. However, the AMB provided greater restraint to anterior tibial translation in both of these tests in comparison to the PLB. The clinical relevance of this study is that an ACL graft that is designed to simulate AMB function would theoretically resist medial and lateral

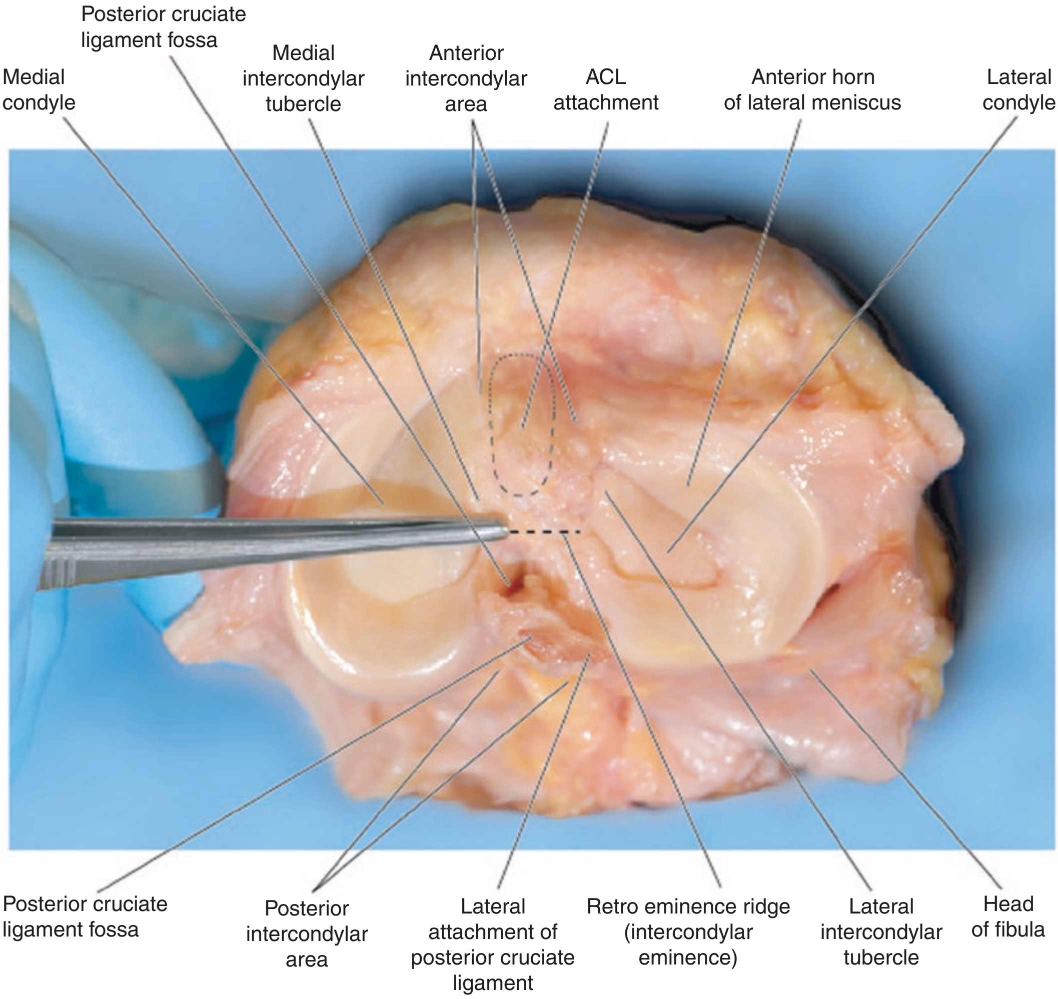

Fig. 1.4 Axial photo of the tibial plateau demonstrating the anterior insertion of the ACL. Notice the ACL's tibial insertion in relation to the medial tibial spine and the retro-eminence ridge (Reprinted from Strickland J, Fester E, Noyes FR (2017) Lateral and posterior knee anatomy. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 23–35)

compartment anterior subluxations and that this is the most ideal placement at the time of surgery.

The mechanical and microstructural properties of three samples within the AMB and PLB were quantified in 16 cadaveric specimens [43]. Mechanical testing was combined with quantitative polarized light imaging to quantify mechanical properties and collagen organization in the ACL simultaneously. The data reflected that these properties did not vary discretely by bundle but rather more gradually across the full span of the ligament. The conclusion was reached that the subregions of the AMB and PLB possess inhomogeneous mechanical and microstructural alignment; analysis of the six subregions showed a continuum across the ligament and not a demarcation between the two bundles. The complex geometry and fiber function of the ACL is not restored with current reconstructive methods, regardless of graft choice or the use of single- or double-bundle techniques [39, 40].

1.2.3 Gender Differences in ACL and Knee Joint Bony Anatomy

Several studies have reported differences related to gender in ACL and knee joint bony anatomy size and structure that could play a role in the disparity in noncontact ACL injury rates [45–49]. For instance, Chandrashekar et al. [46] reported in cadaver knees (<50 years old) that the ACLs in men were significantly larger than the ACLs in women in length (29.82 ± 2.51 mm and 26.85 ± 2.82 mm, respectively, $P = 0.01$), cross-sectional area (midsubstance 83.54 ± 24.89 mm^2 and 58.29 ± 15.32 mm^2, respectively, $P = 0.007$), volume (2967 ± 886 mm^2 and 1954 ± 516 mm^2, respectively, $P = 0.003$), and mass (2.04 ± 0.26 g and 1.58 ± 0.42 g, respectively, $P = 0.009$). Condylar width was also larger in men compared with women (76.06 ± 2.92 mm and 68.97 ± 5.19, respectively, $P = 0.0007$), but no differences were found in notch geometry.

Date from MRI studies have shown that women have smaller-sized ACLs (volume and cross-sectional area), medial femoral condyles, lateral femoral condyles, and bicondylar widths than men [45, 47–49]. Anderson et al. [45] studied the ACL in 50 male and 50 female high school basketball players. Males had significantly larger measurements compared with females in ACL area (48.9 and 36.1 mm^2, respectively, $P < 0.0001$), total condylar width (76 and 67.3 mm, respectively, $P < 0.0001$), lateral condylar width (25.8 and 23.1 mm, respectively, $P < 0.0001$), and notch width (23.7 and 20.5 mm, respectively, $P < 0.0001$). When adjusted for height, the area of the ACL increased as height increased among males, but not among females.

Tibial slope was measured in 452 male and 93 female cadaver specimens (mean age, 36 ± 14 year) using a digital laser that allowed virtual representation of each bone created with a three-dimensional digitizer apparatus [50]. The mean medial tibial slope was greater in females compared with males (7.5° ± 3.8° and 6.8° ± 3.7°, respectively, $P < 0.05$), as was the mean lateral tibial slope (5.2° ± 3.5° and 4.6° ± 3.5°, respectively, $P < 0.05$).

Recent consensus statements promote a relationship between knee joint geometry and higher-risk biomechanics for noncontact ACL injuries [51]. Greater posterior-inferior lateral tibial slopes are associated with greater anterior joint reaction forces, anterior tibial translation, and peak anterior tibial acceleration [52–54]. When combined with a smaller ACL cross-sectional area, these factors are associated with greater peak ACL strains [55].

One study compared male and female cadaveric knees to determine if gender differences existed in ACL structural and material properties [56]. Ten female and ten male knees (mean age, 36 years; range, 17–50) were tested to failure. The female ACLs had lower mechanical properties (14.3% lower stress at failure, 9.43% lower strain energy density at failure, 22.49% lower modulus of elasticity) compared with the male ACLs. The authors reported that the structural properties were weaker in the female specimens even after controlling for age and ACL and body anthropometric measurements.

A multivariate analysis reported that, when adjusted for body weight, predictors of noncontact ACL injuries were ACL volume in both genders (odds ratio [OR] women 0.793, $P = 0.04$; OR men 0.715, $P = 0.05$), femoral intercondylar notch width in women only (OR women 0.469, $P = 0.002$), and thickness of the bony ridge at the anteromedial outlet of the femoral notch in women only (OR 1.686, $P = 0.04$) [49].

Critical Points

- Mean ACL length 32 mm (range, 22–41 mm); width ranges from 7 to 17 mm.
- Origin of ACL on medial aspect of lateral femoral condyle, 18 mm long and 10 mm wide.
- Insertion of ACL on tibia in anterior intercondylar area, oval-triangular pattern, anteroposterior dimension 18 mm, mediolateral dimension 10 mm.
- Disagreement exists on the division of the ACL into two distinct fiber bundles: anteromedial (AM) proximal half of femoral attachment, tightens with knee flexion; posterolateral (PL) distal half of the femoral attachment, tightens with knee extension.
- Reciprocal tightening and relaxation of the AM and PL bundles occur under no anterior loading conditions.

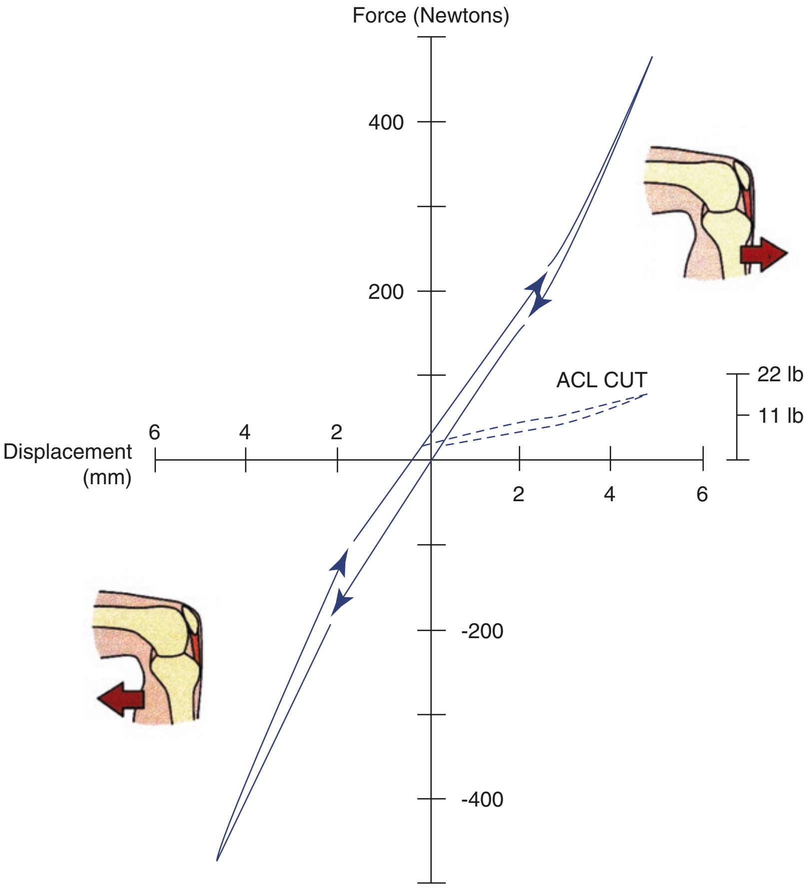

Fig. 1.5 A typical force-displacement curve for anterior-posterior drawer in an intact joint (*solid line*) and after cutting the ACL (*broken line*). The *arrows* indicate the direction of motion (Reprinted from Noyes FR, Grood ES (2017) Knee ligament function and failure. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 37–82)

- Under loading conditions, majority ACL fibers are in load-sharing configuration.
- Characterization ACL into two fiber bundles: gross oversimplification, not supported by biomechanical studies.
- ACL smaller in length, volume, cross-sectional area in women compared with men.

1.3 Biomechanics and Rotational Knee Stability

1.3.1 Primary and Secondary Function of the ACL

The ACL is the primary restraint to anterior tibial translation, providing 87% of the total restraining force at 30° of knee flexion and 85% at 90° of flexion (Figs. 1.5 and 1.6) [57]. A combined secondary restraint to anterior tibial translation is provided by the iliotibial band (ITB), mid-medial capsule, mid-lateral capsule, medial collateral ligament, and fibular collateral ligament. The posteromedial and posterolateral capsular structures provide added resistance with knee extension. Repeated giving-way episodes or failure to successfully reconstruct the ACL may result in loss of the secondary restraints and increased instability symptoms. The failure load and stiffness values of the ACL are 2160 ± 157 N and 242 ± 28 N/mm, respectively [58]. These values decrease with age [40, 59].

The ACL and posterior cruciate ligament are secondary restraints to medial and lateral joint opening and become primary restraints when the collateral ligaments and associated capsules are ruptured. Because the cruciates are located in the center of the knee, close to the center of rotation, the moment arms are approximately one-third of those of the collateral ligaments. Therefore, to produce restraining moments equal to the collateral ligaments, the cruciates must provide a force three times larger than that of the collaterals.

The ACL and lateral knee structures (anterolateral ligament [ALL], ITB, and Kaplan fibers) limit the combined motions of internal rotation and anterior tibial translation, measured by the pivot-shift and/or flexion-rotation drawer tests [60, 61]. The motions that occur during the pivot-shift maneuver are shown in Fig. 1.7 [40]. The pivot-shift rotational subluxation results in giving-way symptoms that require correction by ACL reconstruction. We note that multiple

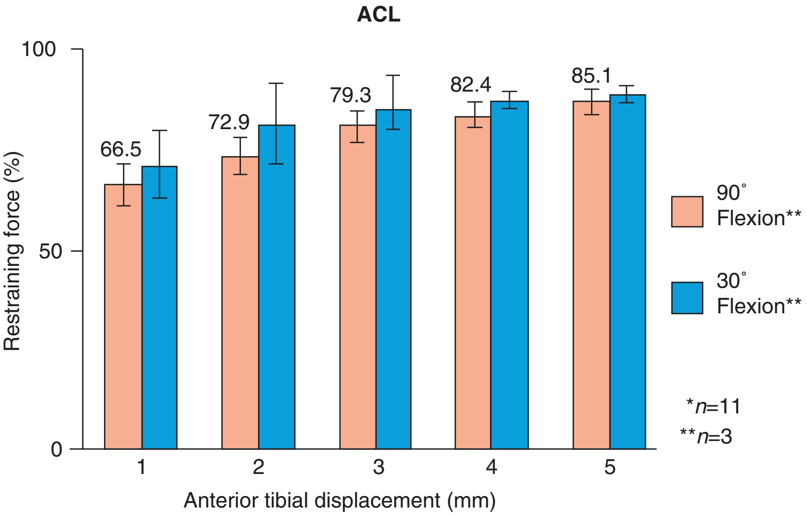

Fig. 1.6 Anterior drawer in neutral tibial rotation. The restraining force of the ACL is shown for increasing tibial displacements at 90° and 30° of knee flexion. The mean value is shown, plus or minus 1 standard error of the mean. Percentage values are given for 90° of flexion. No statistical difference was found between 90° and 30° or between 1 and 5 mm of displacement (Reprinted from Noyes FR, Grood ES (2017) Knee ligament function and failure. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 37–82)

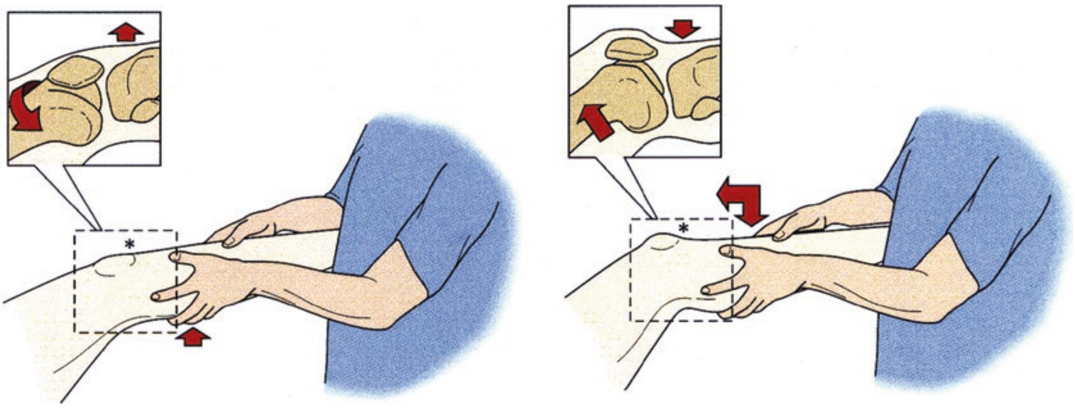

Fig. 1.7 *(Left)* Flexion-rotation drawer test, subluxated position. With the leg held in neutral rotation, the weight of the thigh causes the femur to drop back posteriorly and rotate externally, producing anterior subluxation of the lateral tibial plateau. *(Right)* Flexion-rotation drawer test, reduced position. 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 tibial condyle (Reprinted from Noyes FR, Grood ES (2017) Knee ligament function and failure. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 37–82)

studies over the past decade have shown the importance of ACL graft placement in the anatomic location of its native attachment sites [39]. From a surgical standpoint, these graft placement sites are in the femoral proximal two-thirds (ACL anteromedial portion) and in the central tibia, thereby avoiding a vertical graft placement (in the distal femoral and posterior tibial sites). In a recent robotic study at our center, we demonstrated that a bone-patellar tendon-bone (B-PT-B) ACL reconstruction placed in the anatomic attachment sites restored nearly normal joint kinematics and corrected the pivot-shift subluxation [62].

1.3.2 Rotational Knee Stability

The term *rotational knee stability* is used to describe abnormal joint positions or displacements and not patient complaints of partial or complete giving-way and the activity in which these problems occur (strenuous sports, light sports, or activities of daily living) [63]. In the pivot-shift subluxation event, increased anterior translation of the medial, central, and lateral tibiofemoral compartments occurs [39]. The ACL provides rotational stability to these combined motions. Note that the medial ligamentous structures influence the new center of rotation in the pivot-shift subluxation event. Therefore, a combined injury to both the ACL and medial structures results in the center of rotation shifting far medially (Fig. 1.8), causing a large anterior subluxation of both tibiofemoral compartments. These knees may require surgical restoration of severely injured medial and lateral ligament structures in addition to the ACL to restore knee stability.

A positive pivot-shift test produces a greater anterior tibial subluxation than the Lachman test. This is especially evident when the clinician uses combined anterior tibial loading, internal rotation, and a valgus torque to induce the pivot-shift subluxation. In our laboratory, a study was conducted that used a 6 degrees of freedom robotic knee testing system that applied anterior translation and rotational loading profiles to cadaveric knees [64]. The results were similar to those reached in a study conducted in 1991 of orthopedic surgeons performing pivot-shift tests on an instrumented lower extremity device [65].

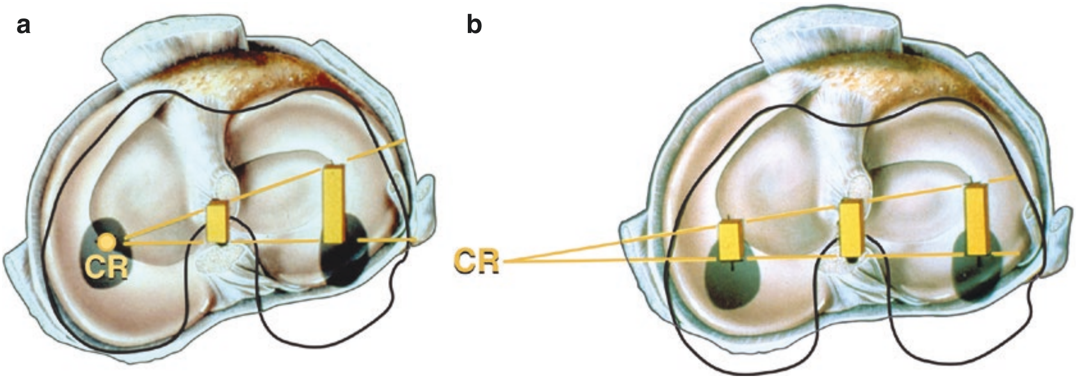

Fig. 1.8 Intact knee and after ACL sectioning: response to coupled motions of anterior tibial translation and internal tibial rotation. (**a**) Intact knee. The center of rotation (CR) may vary between the medial aspect of the posterior cruciate ligament and meniscus border, based on the loads applied and physiologic laxity of the ligaments. (**b**) ACL sectioned; note shift in center of tibial rotation medially. The effect of the increase in tibial translation and internal tibial rotation produces an increase in medial and lateral tibiofemoral compartment translation (anterior subluxation). The millimeters of anterior translation of the tibiofemoral compartments represent the most ideal method to define knee rotational stability. The center of rotation under a pivot-shift type of test shifts to the intact medial ligament structures. If these are deficient, the center of rotation shifts outside the knee joint (Reprinted from Noyes FR, Barber-Westin SD (2017) Anterior cruciate ligament primary reconstruction: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 137–220)

A combined loading profile of anterior translation, internal rotation, and valgus torque (as the knee approached extension) produced the greatest amount of anterior subluxation of the medial and lateral tibiofemoral compartments.

We note that previously published pivot-shift laboratory studies commonly did not report the final anterior position of the medial and lateral tibiofemoral compartments (i.e., only central tibial translation or internal tibial rotation data were provided) [64]. The description of rotational knee stability that occurs in the pivot-shift subluxation event requires precise knee loading conditions and subsequent determination of the anterior translations (subluxations) of the medial and lateral tibiofemoral compartments.

1.3.3 Role of the Anterolateral Ligament Structures

The effect of the ALL and ITB on rotational knee stability with ACL disruptions has received increased emphasis in the past few years. After ACL disruption, a concurrent injury to the ALL produces increases in both the pivot-shift subluxations (conversion to a grade 3 clinical pivot shift) and in the internal rotation limit (Fig. 1.9). Some authors have recommended that concurrent *ALL* reconstruction should be performed with a primary ACL reconstructions in these cases [66, 67], whereas others have stated there is little benefit of this added lateral surgical procedure that may even be deleterious to the joint [68, 69]. At our center, robotic studies were recently conducted that examined the effect of a concurrent ALL reconstruction with an ACL reconstruction in terms of pivot-shift tibiofemoral compartment subluxations and internal tibial rotation limits [68, 69]. Two points from these robotic studies are worth emphasizing. First, a B-PT-B ACL graft was used with high fixation strength (interference screw) that decreased the potential for graft elongation at the fixation site. This is important because the primary benefit of a concurrent ALL reconstruction or ITB tenodesis has been noted in

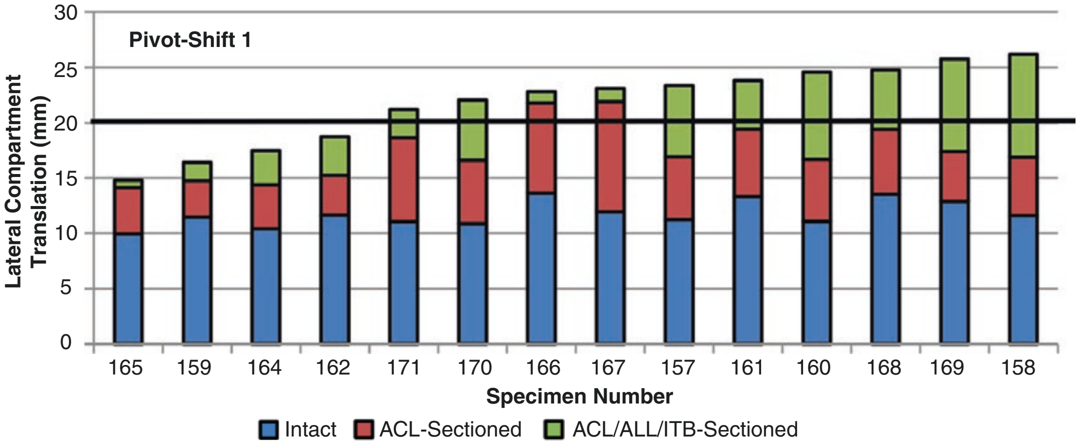

Fig. 1.9 Absolute lateral compartment translation of each specimen shown for intact, ACL-sectioned, and ACL-, ALL-, and ITB-sectioned states for pivot-shift 1 (100-N anterior force, 5-Nm internal rotation torque, and 7-Nm valgus). The bold line at 20 mm indicates the absolute magnitude of lateral compartment translation for a grade 3 pivot shift. Specimens are arranged in increasing order of final lateral compartment translation with the ACL, ALL, and ITB sectioned. This shows the effect of both the ACL sectioning and the ALL and ITB sectioning on the final magnitude of lateral compartment translation, as well as the variability among specimens. The specimens with the ALL and ITB providing a secondary restraint typically had less compartment translation with the ACL sectioned alone (e.g., see specimens 158 and 160). In contrast, specimens 166 and 167, which had very little effect of ALL and ITB sectioning, had the greatest amount of anterior translation with the ACL sectioned alone (Reprinted from Noyes FR, Huser LE, Levy MS (2017) Rotational Knee Instability in ACL-Deficient Knees: Role of the Anterolateral Ligament and Iliotibial Band as Defined by Tibiofemoral Compartment Translations and Rotations. J Bone Joint Surg Am 99 (4):305–314)

studies that used lower-strength ACL grafts (STG or allografts) that have a higher incidence of early clinical failure postoperatively [67, 70].

The second point relates to the simulation of the pivot-shift subluxation event under robotic loading conditions; the most ideal type of loading involves a 4-degree-of-freedom displacement as performed in our laboratory (Fig. 1.10) [44, 62, 64]. This model combines anterior tibial translation, internal tibial rotation, and valgus loading as the knee cycles into knee extension (subluxation), with reversal of these loads with knee flexion (reduction). This model produces maximum anterior subluxation of the medial and lateral tibiofemoral compartments [64]. Methods used in other laboratories incorporated a 3-degree-of-freedom model that did not include anterior tibial loading. In these studies, internal tibial rotation (in the absence of an anterior tibial load) actually reduced the medial tibiofemoral compartment and markedly limited the abnormal translation of the central tibial compartment. This loading sequence is not recommended and has resulted in conflicting recommendations for ACL grafts because it produces very low ACL graft forces and elongations that do not reproduce or simulate clinical pivot-shift loading conditions.

With the simulation of the pivot-shift test using the 4-degree-of freedom displacement model, we conducted a robotic analysis on the

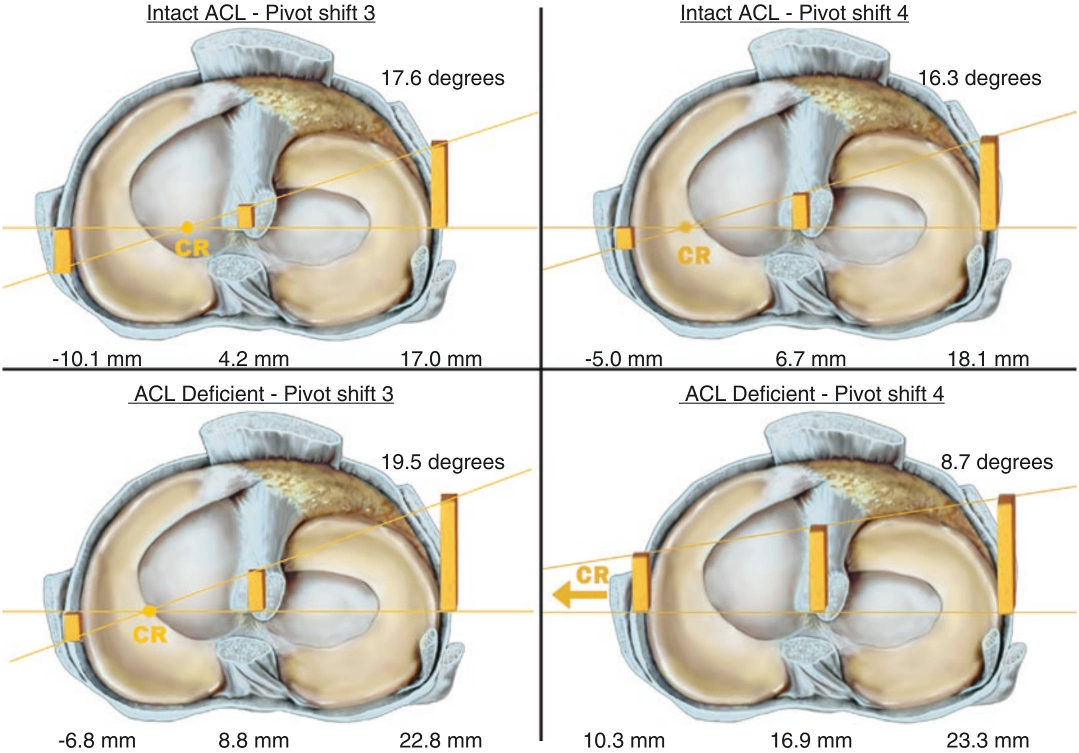

Fig. 1.10 A representative right knee specimen showing compartment translations and tibial rotation under two loading conditions: pivot-shift 3 and pivot-shift 4. In the pivot-shift 3 loading, there is a coupled internal rotation-valgus loading with a high internal rotation torque. There is no subluxation of the medial tibiofemoral compartment. In contrast, in the pivot-shift 4 loading, there is a coupled anterior tibial translation-internal rotation (low) and valgus loading. 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 Nm internal rotation, and 7 Nm valgus. Loading conditions for pivot-shift 4 were 100 N anterior, 1 Nm internal rotation, and 7 Nm valgus. *CR* center of tibial rotation (Reprinted from Noyes FR, Barber-Westin SD (2017) Anterior cruciate ligament primary reconstruction: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 137–220)

function of the ALL structures [68, 69, 71]. The results demonstrated that removal of the ALL or ITB alone did not increase internal tibial rotation as long as the ACL was intact. Even with removal of both anterolateral structures, the increase in the degrees of internal tibial rotation was small (1.7°, 4.5°, and 3.9° at 25°, 60°, and 90° of knee flexion, respectively) and would not be detected clinically [71]. In addition, with the ACL intact, sectioning both the ALL and ITB did not lead to an increase in tibiofemoral compartment translations in the pivot-shift tests. We concluded that the anterolateral structures are not primary restraints for the pivot-shift subluxation event.

In another robotic study at our center, an ALL reconstruction was performed with an ACL reconstruction to determine if there was a beneficial effect of the concurrent lateral reconstruction [68]. The ALL reconstruction did correct the small increase in degrees of internal tibial rotation at high knee flexion angles. However, the ALL reconstruction had no effect on the pivot-shift tests in limiting anterior tibiofemoral translations and had only a modest effect in decreasing ACL graft loads. It was concluded that these small changes did not support the routine addition of a concurrent ALL surgical procedure. It is noted that there may be select instances to incorporate an ALL reconstruction, such as in knees with a grade 3 pivot shift in which a lower-strength ACL graft is used (small STG or allograft) or in revision knees in which the surgeon desires to use a combined intra-articular and extra-articular graft configuration.

Critical Points

- ACL primary restraint anterior tibial translation provides 87% total restraining force.
- ACL failure load 2160 ± 157 N, stiffness 242 ± 28 N/mm.
- ACL and PCL are secondary restraints to medial and lateral joint opening and become primary restraints when collateral ligaments and capsules are ruptured.
- ACL and lateral knee structures limit combined motions of internal tibial rotation and anterior tibial translation.
- In the pivot-shift subluxation event, increases occur in anterior tibial translation of the medial, central, and lateral tibiofemoral compartments.
- ACL provides rotational stability to these combined motions.
- Effect of the anterolateral structures (ALL) has received increased emphasis.
- Our laboratory studies used a 4-degree-of-freedom model that combined anterior tibial translation, internal tibial rotation, and valgus loading as the knee cycles into knee extension and flexion.
- Removal of the ALL or iliotibial band alone did not increase internal tibial rotation as long as the ACL was intact. The ALL and ITB (Kaplan fibers) are not primary restraints for pivot-shift subluxation.
- ALL reconstruction with ACL reconstruction is usually not required under conditions of a well-placed and fixated bone-patellar tendon-bone graft.
- ACL graft placement sites are in the femoral proximal two-thirds (ACL anteromedial portion) and in the central tibia, thereby avoiding a vertical graft placement (in the distal femoral and posterior tibial sites).

1.4 Common ACL Injury Mechanisms

1.4.1 Current Proposed Mechanisms

ACL injury mechanisms are influenced by a multitude of factors, including anatomy and biomechanics already discussed, in addition to neuromuscular, genetic, hormonal, and other factors that are reviewed in detail in *Part II*. In the female athlete, the combination of a structurally weaker ACL and poor neuromuscular movement and landing patterns appear to have the largest influence on noncontact injuries. In all athletes, knee joint stability during weight-bearing activities is influenced by the muscles, ligaments, and bony geometry which act together to resist potentially dangerous forces

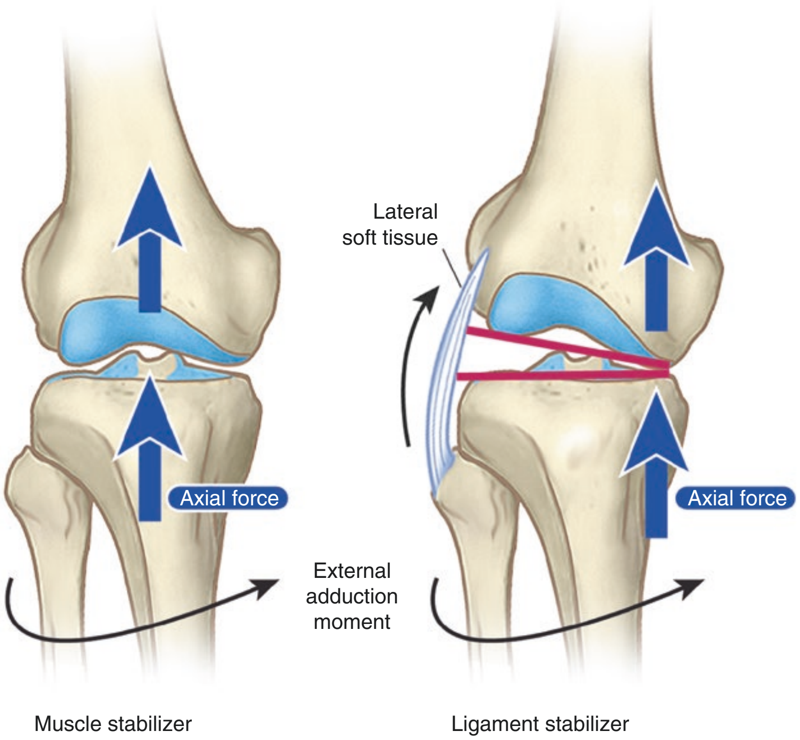

Fig. 1.11 *Left*, knee joint stability is influenced by the muscles, ligaments, and bony geometry, which act together to resist external adduction moments that are incurred during weight-bearing activities. *Right*, an abnormally high adduction moment may result in laxity of the lateral soft tissues and loss of normal lateral tibiofemoral joint contact. Termed *lateral condylar lift-off*, this phenomenon increases the potential for an ACL rupture, especially if the knee is in 30° of flexion or less (Reprinted from Barber-Westin SD, Noyes FR (2010) Lower limb neuromuscular control and strength in prepubescent and adolescent male and female athletes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. Saunders, Philadelphia, pp. 379–403)

and external adduction moments (Fig. 1.11). The mechanisms of noncontact ACL injuries involve multiplanar loadings, with approximately two-thirds of ruptures occurring during noncontact situations while an athlete is cutting, pivoting, accelerating, decelerating, or landing from a jump [8, 9, 72]. Common injury circumstances have been described for both men and women, including perturbation of the athlete from an opponent [8, 10, 11]. Perturbation situations include being pushed or shoved just before the injury, avoiding a player in close proximity usually while playing offense, or attempting to avoid a collision with another player. These circumstances cause an athlete to be off-balance or lose control and alter their normal neuromuscular mechanics. Numerous abnormal biomechanical loads and body positions producing noncontact ACL injuries have been observed and include [9, 73]:

1. Anterior shear force, arising from large quadriceps contractions that occur with low knee flexion or hyperextension and lack of hamstrings muscle activation
2. Valgus collapse at the knee joint (whether cause or result of injury unclear)
3. Transverse plane tibial rotation
4. Foot placed far from the center of body mass
5. Posteriorly directed or erect trunk position
6. Hip internal rotation
7. Decreased knee and hip flexion angles
8. Excessive hip adduction

The so-called quadriceps dominance mechanism for ACL injury is important. With the athlete decelerating or stopping suddenly, there is a definite tendency to displace the foot and knee in front of the center of the body's mass. To maintain balance, a sudden and forceful quadriceps contraction occurs that produces an anterior tibial translation which can be sufficient to cause an ACL rupture.

Markolf et al. [74] measured in vitro forces in cadaver ACL specimens during isolated and combined loading states. A high valgus or varus moment increased the risk for medial or lateral tibiofemoral joint lift-off and the potential for a knee ligament rupture. Abnormally high knee adduction moments may result in laxity of the lateral soft tissues and loss of normal lateral tibiofemoral contact, termed lateral condylar lift-off. These investigators reported that increases in ACL forces were greater when a valgus or varus moment was applied along with an anterior tibial translation compared to when an anterior tibial translation was applied alone. Many noncontact ACL tears have been noted to involve loads in multiple planes, as was suggested in this early laboratory study.

More recent studies have simulated hypothesized high-risk movements (such as pivoting and single-leg landing) using cadaveric and computer models to determine how the ACL is loaded in vitro [75–79]. ACL strain increases with anterior tibial loading and combined knee-abduction and knee-internal rotation moments. For example, Shin et al. [79] used a validated simulation model of a three-dimensional dynamic knee joint to predict ACL strain during a single-leg landing. The results demonstrated that combined valgus moment and tibial internal rotation moment that occurred in the knee joint on landing significantly increased the peak strain in the ACL. The effect of these combined rotation moments was greater than the effect of either rotation moment acting alone, which did not produce ACL strain levels expected to cause ACL rupture.

Debate exists regarding which neuromuscular mechanics are present at the time of the injury and which occur just after the ACL rupture. In the first study that used videotape analysis of sequences of ACL injuries, Olsen and associates [80] admitted that "whether the consistent valgus collapse observed in the videos was actually the cause of injury or simply a result of the ACL being torn is open for discussion." Hashemi et al. [81] proposed a framework for establishing the viability of a noncontact ACL injury mechanism that included the questions shown below:

1. What is the inciting event?
2. What are the muscle forces and joint torques/loading necessary to produce an ACL injury? Are these proposed injury forces physiological?
3. Does the proposed mechanism meet the timing requirement for ACL injury?
4. What is the role of fatigue on neuromuscular control of the muscles that span the knee, hip, and ankle joints?
5. How do sagittal and transverse kinematics of the hip as well as ankle complex kinematics alter ACL loading?
6. What is the role of the tibial plateau geometry in loading the ACL?
7. What is the effect of knee laxity on ACL injury mechanism?
8. What causes the abnormal knee kinematics during ACL injury?
9. How does the mechanism explain the existing sex-based disparity in ACL injuries?

These authors presented the mechanisms which had been discussed in the literature to date, including excessive quadriceps force producing an anterior tibial shear force, knee-abduction moments (valgus), and tibial rotation.

1.4.2 Effect of Muscle Forces and Knee Flexion Angle

The ACL is strained when the quadriceps are contracted with the knee near full extension. Cadaver studies [82–84] have shown that isolated quadriceps isometric and isotonic contractions increase ACL strain from 0° to 45° of flexion, with the greatest magnitude occurring at full knee extension. DeMorat et al. [82] postulated that the force caused by a high quadriceps contraction with the knee in only slight flexion could induce ACL rupture. In the laboratory, a 4500 N quadriceps contraction in a cadaver knee in 20° of flexion resulted in a complete ACL disruption at the femoral insertion site in 6 of 11 knees and a partial ACL injury in 3 other knees. Fleming et al. [85] reported that the gastrocnemius muscle is an ACL antagonist when the knee is near full extension. A co-contraction of the gastrocnemius and the quadriceps loads the ACL to a greater extent than isolated contractions of these muscle groups at 15° and 30° of flexion.

The hamstring musculature is important in stabilizing the knee joint [86–88] but has a marked functional dependence on the angle of knee flexion and degrees of external tibial rotation (Fig. 1.12). These muscles actively oppose extension by stabilizing the knee posteriorly and preventing knee hyperextension and anterior subluxation of the tibia. In addition, they actively oppose external tibial rotation. The mechanical advantage of the sartorius, gracilis, and semitendinosus muscles increases as the knee goes into further flexion. For instance, at 0° of extension, the flexion force is reduced to 49% of that measured at 90° of flexion. In addition, a quadriceps-hamstrings co-contraction cannot reduce ACL strain from full extension to approximately 20° of flexion [89, 90].

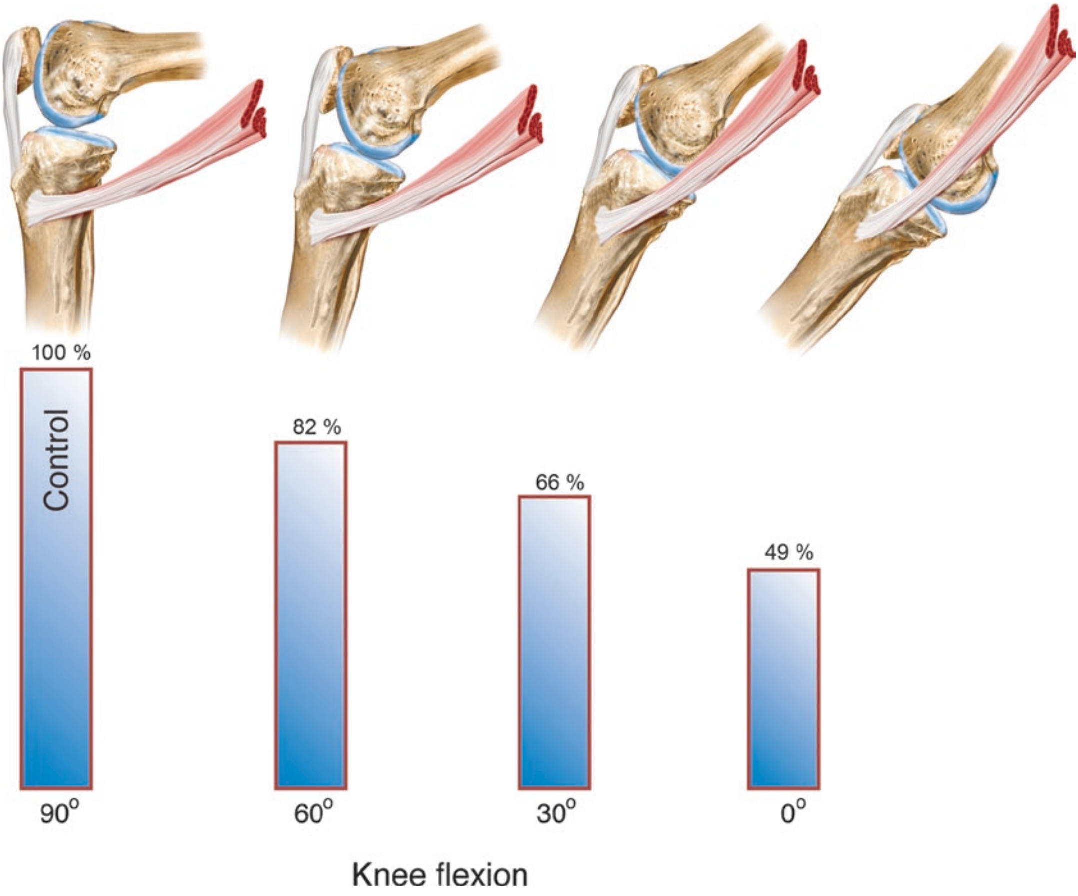

Fig. 1.12 Pes anserine (sartorius, gracilis, semitendinosus muscles) flexion forces. Stick figures show that knee extension yields a decrease in insertion course angles with respect to the tibia. Resulting loss in mechanical advantage is indicated by reduced flexion forces with extension ($P < 0.05$) (Reprinted from Barber-Westin SD, Noyes FR (2017) Scientific basis of rehabilitation after anterior cruciate ligament autogenous reconstruction. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 268–292)

A decrease in the strength of the hamstrings relative to the quadriceps (hamstrings/quadriceps [H/Q] ratio) is believed to be a risk factor for ACL injuries. We previously reported significant gender differences in isokinetic muscle strength during adolescence in 1030 athletes aged 9–17 [91]. Significantly higher quadriceps and hamstrings peak torques were found in males compared with females from ages 14–17. A systematic review of 22 studies involving 1568 subjects revealed significantly higher isokinetic H/Q ratios in males compared with females at speeds of 60°/s, 120°/s, 300°/s, and 360°/s [92]. Although males demonstrated a significant increase in the H/Q ratio with increasing test speed velocities (that approach those of functional activities), women did not demonstrate similar increases (Fig. 1.13).

Pollard et al. [93] studied the effect of knee and hip flexion angles during the deceleration phase of a drop-jump task on knee kinematics and moments. Subjects that used less knee and hip flexion on landing demonstrated increased knee valgus angles, knee adductor moments, and vastus lateralis activity compared with athletes who landed with greater hip and knee flexion. This demonstrates that the quadriceps dominant pattern is influenced by the inability of the hip extensors to absorb energy when athletes land in low hip flexion angles.

Colby et al. [94] measured hamstring and quadriceps muscle activation and knee flexion angles during eccentric motion of sidestep cutting, cross-cutting, single-leg stopping, and landing/pivoting in nine male and six female collegiate athletes. A high quadriceps muscle activation occurred just before foot strike and peaked in mid-stance. The peak quadriceps muscle activation occurred between 39° (stopping) and 53° (cross-cutting) of knee flexion and averaged between 126% (landing) and 161% (stopping) of that measured in a maximum isometric contraction. Hamstring muscle activation was submaximal at and after foot strike. The minimal hamstring muscle activation occurred between 21° (stopping) and 34° (cutting) of knee flexion and averaged between 14% (landing) and 40% (cross-cutting) that of a maximum isometric contraction. The knee flexion position that foot strike occurred during all four activities averaged 22° (range, 14° on stopping to 29° on cross-cutting). The authors concluded that the

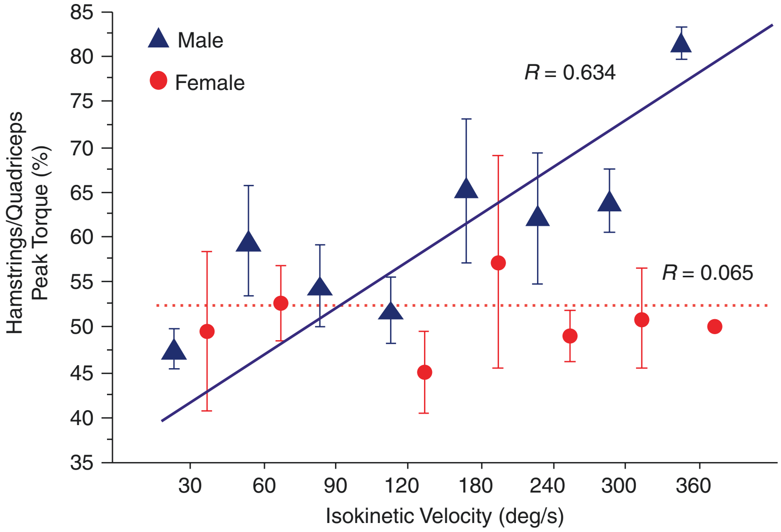

Fig. 1.13 Hamstrings/quadriceps ratio in female and male subjects diverges with increasing angular velocity. A significant difference in the ratio in males was found between 30°/s and 60°/s, 180°/s, 240°/s, 300°/s, and 360°/s ($P < 0.05$). There were no significant differences between the ratios in females at any test velocity. Males had significantly greater ratios than females at all speeds except 30°/s (Reprinted from Hewett TE, Myer GD, Zazulak BT (2008) Hamstrings to quadriceps peak torque ratios diverge between sexes with increasing isokinetic angular velocity. J Sci Med Sport 11 (5):452–459)

combination of the high level of quadriceps activity, low level of hamstrings activity, and low angle of knee flexion during eccentric contractions in these maneuvers could produce significant anterior translation of the tibia.

1.4.3 Video Analysis of ACL Injuries

Several investigators have analyzed video sequences of ACL injuries to describe common injury mechanisms and lower extremity positions and angulations at the estimated time of ligament rupture and 30 to 50 milliseconds (ms) after the injury (Table 1.1) [10, 72, 80, 95–100]. The majority of studies to date have used simple visual inspection of video footage that involves problems related to quality and resolution of the video images and number of camera views available. Even with computerized methods of measuring joint kinematics, only estimates can be made regarding the exact moment the ACL

Table 1.1 Video analysis studies of ACL injuries

Study	Cohort	Video analysis methods	Noncontact ACL injury mechanisms	Knee positions	Hip positions	Foot/ankle positions
Brophy et al. [96]	32 males 23 females Soccer players	Two reviewers, footage from one to three cameras. Estimated knee flexion angle in 30° increments (sagittal), coronal plane alignment (abducted, adducted, or neutral), foot position (toe, heel, flat)	Perturbation by opposing player noted in 83%; 71% playing defense	Flexion (0–30°): 71% Valgus: 58%	Flexed: 88% Abducted: 83%	58% landed flat footed
Walden et al. [72]	39 males Professional soccer players	Five reviewers, footage from one to five cameras. Assessed real-time and slow motion footage. Joint flexion angles estimated to nearest 5° at five time periods	79% playing defense. Most common during pressing, regaining balance after kicking, landing after heading. "Substantial" hip abduction (>20°), knee valgus, ankle eversion noted	Flexion: <20° 74% Flexion: <10° 26%. Valgus: 79%, no overt dynamic collapse	Flexion: <40° 55% <30° 28% <20° 17%	44% landed on toes, 39% on heel, 17% flat footed
Koga et al. [11]	10 females (7 handball, 3 basketball players)	Model-based image-matching technique to recreate three-dimensional knee kinematics, footage from ≥2 cameras	All players were handling the ball, injured while cutting in 7 and landing onto single leg in 3. Six players contact with opponent on torso	Flexion: 11–30° IC, increased 24° at 40 ms Abduction angle: neutral IC, increased 12° at 40 ms Tibial rotation: 5° ER IC and then IR 8° at 40 ms and then ER of 17°	NA	NA

(continued)

Table 1.1 (continued)

Study	Cohort	Video analysis methods	Noncontact ACL injury mechanisms	Knee positions	Hip positions	Foot/ankle positions
Boden et al. [10]	29 athletes 27 controls Various sports	One reviewer, footage from sagittal or coronal view. Videos converted into five still frames beginning with IC. Computer measurements made of foot, knee, and hip angles	Perturbation by opposing player in majority while playing offense. Females performing deceleration motion, males jumping/landing	No difference knee flexion subjects vs. controls. No difference IC knee-abduction subjects vs. controls, but subjects had greater abduction frames after IC	Higher hip flexion subjects vs. controls. No difference hip abduction subjects vs. controls	Landed either hindfoot or flat-footed position. Ankle less planter-flexed subjects vs. controls
Krosshaug et al. [99]	22 females 17 males Basketball players	Six reviewers, footage from one to four cameras. Assessed real-time and slow motion footage. Analyzed IC and 50 ms after time (estimated) injury. All joint angles estimated	Majority players handling ball when injured; perturbation by opposing player in most. Injured on landing or cutting	Estimated flexion IC: 15° females, 9° males; 50 ms 27° females, 19° males Estimated valgus IC: 4° females, 3° males; 50 ms 8° females, 4° males	Estimated flexion IC: 27° females, 19° males; 50 ms 33° females, 22° males Estimated abduction 8° to 19° (range −7° to 48°)	NA

ER external rotation, *IC* initial contact, *IR* internal rotation, *ms* milliseconds

rupture occurred and positions of the hip and knee at initial contact (IC) with the ground, time of injury, and thereafter (for instance, 30 ms after the injury).

One investigation attempted to quantify video sequences using a computerized three-dimensional analysis technique that replicated the lower limb and knee joint motions that occurred during the ACL injuries [11]. Koga et al. [11] analyzed ten ACL injury sequences from female handball and basketball players. Seven injuries occurred during cutting and three during single-leg landings. The injured player was handling the ball in all cases. The data regarding knee flexion angles, knee adduction and abduction angles, and tibial rotation demonstrated that, at IC, a neutral limb position was present. The knee-abduction angle was neutral (mean 0°; range, −2° to 3°), and the tibial rotation angle was slightly external (mean, 5°; range, −5° to 12°). Knee flexion averaged 23° (range, 11–30°). At approximately 40 ms later, a mean increase in the knee flexion angle of 24° (range, 19–29°), a mean increase in the abduction (valgus) angle of 12° (range, 10–13°), and a change in tibial rotation from 5° external to 8° internal (range, 2–14°) were reported. There were "remarkably consistent descriptions of knee joint kinematics" from all ten injury situations and the conclusion was reached that the ACL injuries most likely occurred within 40 ms after IC. The authors acknowledged the potential for errors and "limited precision" in performing the model matching using standard television broadcasts.

Walden et al. [72] analyzed videotapes of 39 ACL injuries in male professional soccer players. These authors noted that, although a valgus knee position was frequently seen, a dynamic valgus collapse rarely occurred (3 of 39 cases). These authors questioned whether the overt valgus collapse frequently seen in other studies of female athletes was a gender-related consequence of the injury and not a mechanism that caused the ACL rupture.

Boden et al. [10] analyzed videotapes of ACL injuries in 29 athletes to conduct an analysis of the position of the hip, knee, and ankle from either a coronal or sagittal view. The majority of subjects (96%) had an opposing player in close proximity just before or during the injury, and most were playing offense, both of which could have caused an alteration in the normal hip, knee, and foot positions. When the injury occurred, the female subjects typically were performing a deceleration motion, whereas the male players were performing strenuous jumping and landing maneuvers. Compared with a control group analyzed during similar athletic motions, the subjects landed in a flat-footed position, with little ankle plantar flexion. This landing position was postulated to lead to a lack of energy dissipation by the gastrocnemius-soleus complex, thereby increasing forces to the knee. Higher hip flexion angles were noted as well for the subjects; however, there were no significant differences in knee flexion or abduction angles at IC. Knee-abduction angles progressively increased in the subjects, which was more evident in the female athletes than the male athletes.

Krosshaug and associates [99] analyzed video footage of 17 male and 22 female basketball players who sustained ACL ruptures and reported that opponents were in close proximity in nearly all of the injury situations. Knee collapse into valgus was noted in 53% of the female players and in 20% of the male players. The collapse was described as a combination of hip internal rotation, knee valgus, and external tibial rotation. These authors also reported that females landed with greater hip and knee flexion than male players. However, the reliability of the study's visual inspection approach to measuring these flexion angles was questionable. Another investigation reported consistent underestimates of nearly 20° of knee flexion when comparisons were made of measurements obtained from video and the actual flexion angles that occurred during running and cutting [101].

Olsen et al. [80] analyzed videotapes of 19 noncontact ACL injuries in female team handball players. The most common injury mechanism was a plant-and-cut movement in which a forceful valgus collapse of the knee and tibial rotation (internal or external) with the knee close to full extension was noted. The foot was firmly planted on the handball court and was well outside of the center of the body in nearly all cases. The authors acknowledged that it was unknown whether the valgus position of the knee caused the ACL injury or occurred as a result of the injury. The majority of subjects were out of balance as a result of being pushed or held by an opponent or trying to evade a collision, which caused the unusually wide foot position relative to the knee and center of the body.

1.4.4 Authors' Proposed Mechanisms of Noncontact ACL Ruptures

From the videotaped analyses of ACL injuries, it appears that the amount of time in which an ACL rupture occurs ranges from 17 to 50 ms after initial ground contact [11, 99]. Unfortunately, many problems exist with video analysis studies, including the most sophisticated to date which used model-based image-matching techniques. These include the difficulty in assessing joint kinematics from standard television broadcast tapes and the small number of injured athletes studied. One study admitted to a problem with reliability of the video measurement methods, with consistent underestimation of knee and hip flexion angles and unreliable data with regard to knee-abduction and rotation angles [99]. The lack of control subjects performing similar athletic maneuvers without sustaining an ACL injury is another problem because it remains unclear if similar knee flexion angles, abduction angles, and tibial rotation might exist. Limited data have been presented related to hip and ankle flexion angles and rotation. The exact time of the ACL rupture cannot be determined.

We believe that a noncontact ACL rupture occurs immediately following initial foot strike (commonly with a flatfoot position) due to internal rotation and adduction of the hip, high quadriceps forces, and a knee flexion angle <30°. The subsequent knee-abduction (valgus) position then occurs as a result of the pivot-shift subluxation event just after the ACL has ruptured.

Regardless of the exact amount of time in which an ACL rupture occurs or the responsible mechanisms from multiple planes, there is no doubt that there is not enough time for an athlete to alter the body or lower extremity position in a preventative effort. In order to have a significant impact on reducing the incident rate of this injury, we believe that a training program must employ a multifaceted approach in correcting all of the potential neuromuscular problems present. This includes teaching athletes to control the upper body, trunk, and lower body position, lower the center of gravity by increasing hip and knee flexion during activities, and develop muscular strength and techniques to land with decreased ground reaction forces [9, 102]. In addition, athletes should be taught to preposition the body and lower extremity prior to initial ground contact to obtain the position of greatest knee joint stability and stiffness. In later chapters, the reader will note that it is possible in many athletes to alter potentially dangerous positions with appropriate training and instruction.

Critical Points

- 2/3 ACL tears noncontact while cutting, pivoting, accelerating, decelerating, or landing from a jump.
- Perturbation of athlete from an opponent commonly occurs.
- At the time of or just prior to ACL injury:
  - Reduced knee flexion and ankle plantar angles
  - Increased hip flexion angles, hip internal rotation, internal, or external tibial rotation
  - Valgus collapse at knee
  - Excessive quadriceps force produces anterior tibial shear force
- Video analyses ACL injuries:
  - ACL injured ~40 ms from initial foot contact
  - Females deceleration motion, males jumping/landing
  - Foot outside of center of body, firmly planted
- Proposed mechanisms:
  - ACL rupture occurs 17–50 ms after initial ground contact.
  - Immediately following initial foot strike: internal hip rotation, excessive quadriceps forces, low knee flexion angle (<30°).
  - Creates knee-abduction (valgus) position that occurs due to pivot-shift subluxation.

1.5 The Gender Disparity in ACL Injury Rates

A study from our center published in 1994 was one of the first to report the gender disparity in ACL injury rates in soccer players using player hours (or athlete exposures [AE]) to calculate injury rates [23]. A total of 300 indoor soccer games encompassing 2700 player hours were monitored for injuries. Female players had nearly six times the rate of serious knee ligament injuries compared with male players ($P < 0.01$). Since this study, multiple investigations have reported gender disparity in ACL injury rates in high school athletes (Table 1.2) [8, 24, 103–110], collegiate athletes (Table 1.3) [22, 24, 103, 111–113], US military academies [114–117], and adult athletes [118, 119].

Stanley et al. [24] used two injury surveillance programs to determine ACL injury rates among high school and collegiate athletes. Data from the National Athletic Treatment, Injury and Outcomes Network from 2011–2012 through the 2013–2014 academic years (100–196 high schools) and the NCAA Injury Surveillance Program from 2009–2010 through the 2013–2014 academic years (78–105 colleges) were analyzed for basketball, lacrosse, soccer, and softball/baseball (Table 1.2). Female athletes had significantly greater incidence rates for ACL injuries compared with male athletes at both the high school and collegiate levels for nearly all sports studied.

Table 1.2 Incidence and rates of ACL injuries in high school sports per 1000 athlete exposures

Sport	Study	Study academic years	Female rate	Male rate	Female/male rate ratio
Basketball	Stanley et al. [24]	2009–2014	0.12	0.03	3.7
	Beynnon et al. [103]	2009–2011	0.06	0.04	1.5
	Joseph et al. [8]	2007–2012	0.09	0.02	5.0
	Pfeiffer et al. [110]	1996–1997	0.11	NA	NA
	Hewett et al. [106]	NA (1 year)	0.29	0	0
	Messina et al. [109]	NA (2 years)	0.13	0.04	3.8
	Gomez et al. [104]	1993–1994	0.13	NA	NA
Soccer	Stanley et al. [24]	2009–2014	0.17	0.09	1.9
	Beynnon et al. [103]	2009–2011	0.13	0.03	4.3
	Joseph et al. [8]	2007–2012	0.09	0.04	2.4
	Mandelbaum et al. [108]	2000–2001	0.49	NA	NA
	Pfeiffer et al. [110]	1996–1997	0.11	NA	NA
	Hewett et al. [106]	NA (1 year)	0.22	0.12	1.8
Lacrosse	Stanley et al. [24]	2009–2014	0.32	0.13	2.4
	Beynnon et al. [103]	2009–2011	0.07	0.06	1.2

NA not available

Table 1.3 Incidence and rates of ACL injuries in collegiate sports per 1000 athlete exposures

Sport	Study	Study academic years	Female rate	Male rate	Female/male rate ratio
Basketball	Stanley et al. [24]	2009–2014	0.19	0.07	2.8
	Hootman and Helmick [152]	1988–2004	0.23	0.07	3.3
	Agel et al. [111]	1990–2002	0.16	0.04	4.6
	Mihata et al. [113]	1989–2004	0.28	0.08	3.5
	Arendt and Dick [22]	1989–1993	0.29	0.07	4.1
Soccer	Stanley et al. [24]	2009–2014	0.25	0.06	4.1
	Hootman and Helmick [152]	1988–2004	0.28	0.09	3.1
	Agel et al. [111]	1990–2002	0.13	0.04	3.3
	Mihata et al. [113]	1989–2004	0.32	0.12	2.7
	Arendt and Dick [22]	1989–1993	0.31	0.13	2.4
Lacrosse	Stanley et al. [24]	2009–2014	0.09	0.11	0.8
	Hootman and Helmick [152]	1988–2004	0.17	0.12	1.4
	Mihata et al. [113]	1989–2004	0.18	0.17	1.0
Softball/ baseball	Stanley et al. [24]	2009–2014	0.07	0.01	6.6
	Hootman and Helmick [152]	1988–2004	0.08	0.02	4.0

Joseph et al. [8] analyzed ACL injury data from 9 sports collected through the National High School Sports-Related Information Online program from 100 high schools from 2007–2008 through the 2011–2012 academic years. A total of 617 ACL injuries were reported during 9,542,180 AEs. Female athletes had 5 times the incidence of ACL injuries compared with male athletes in basketball and 2.5 times the incidence of males in soccer. A meta-analysis of nine studies by Gornitzky et al. [105] reported that high school female athletes had 3.8 times the incidence of ACL injuries compared with male athletes in basketball and 3.7 times higher incidence in soccer.

Hootman et al. [112] summarized 16 years of NCAA data in 15 different sports, assessing over one million AEs. Women's gymnastics had the highest ACL injury rate (0.33 per 1000 AE), which was similar to men's spring football. Female basketball players had a threefold higher ACL injury incidence compared with male players (0.23 versus 0.07 per 1000 AEs), as did female soccer players compared with their male counterparts (0.28 versus 0.09 per 1000 AEs). The rate of ACL injuries increased 1.3% on average per year over the 16-year period. Agel et al. [111] reviewed 13 years of NCAA injury data (1990–2002) from 6176 schools and reported a gender disparity in ACL injury rates between collegiate basketball and soccer players. The authors reported that, regardless of the mechanism of injury, female soccer and basketball players had a significantly greater incidence of ACL tears than male players ($P < 0.01$).

Mountcastle et al. [116] examined ACL injuries sustained from 1994 to 2003 at the US Military Academy at West Point. There were significantly higher ACL injury rates in women compared with men in gymnastics (0.24 and 0.04 per 1000 exposures, respectively, $P = 0.001$) and the military indoor obstacle course test (0.94 and 0.25 per 1000 exposures, respectively, $P = 0.02$). In examining noncontact ACL injuries, the female-to-male incidence ratios were 4.95 for gymnastics, 3.72 for the obstacle course test, 3.01 for basketball, 1.71 for handball, and 1.27 for soccer.

Prodromos et al. [120] conducted a meta-analysis entailing 33 articles to test the hypothesis that the incidence of ACL tears would show variation by sport, gender, and effect of ACL intervention training programs. The mean ACL injury rate for females was significantly greater than males in basketball (0.28 and 0.08, respectively, $P < 0.0001$), soccer (0.32 and 0.12, respectively, $P < 0.0001$), and handball (0.56 and 0.11, respectively, $P < 0.0001$). Pooled data from intervention programs from five studies [106, 108, 110, 121, 122] showed that neuromuscular training was effective in significantly reducing the ACL tear rates in soccer and basketball.

Critical Points

- ACL incidence rates, females compared with males:
  - Indoor soccer, adults: 6× greater
  - High school: basketball 3.7–5× greater, soccer 2× greater
  - NCAA: basketball 3–4.5× greater, soccer 2.5–4× greater
  - US Military Academy: gymnastics 5× greater, obstacle course 3.7× greater, basketball 3× greater
- Meta-analysis 33 articles: females 3× greater basketball and soccer, 5 x greater handball

1.6 Can ACL Injury Rates Be Reduced?

Several of the proposed factors that may be responsible for the gender disparity in ACL injury rates are discussed in *Part II*. The question of what places female athletes in certain sports at a higher risk for sustaining a noncontact ACL injury than male athletes represents an ongoing dilemma not yet answered. The major research emphasis to date has focused on factors related to anatomy, neuromechanical (neuromuscular and biomechanical), hormonal fluctuations [123], and muscular fatigue [124]. Fewer studies have examined the influence of genetics [125] and playing surface [126–129], and no investigations to date have examined the effects of footwear or climate conditions. Other potential risk factors such as neurocognition deficiencies, chronic sleep deprivation, poor nutrition and eating disorders, substance use and abuse, overtraining, stress, and depression have yet to be explored in detail [130, 131]. Recent consensus statements have identified the need for multivariate analyses that take into account all of these potential factors to further advance knowledge related to screening and injury prevention training [51].

The impact of ACL injuries, including the high risk of premature osteoarthritis, is discussed in *Part I*. While ACL natural history studies vary regarding the reported percentages of patients who suffer from repeat instability, swelling, associated or subsequent meniscus injuries, symptoms with athletic and daily activities, and alterations in muscle activation patterns and neuromuscular control, the general consensus is that this injury is the cause of long-term problems in the knee joint [17, 132]. Even with a “successful” reconstruction, the cost of treatment, loss of participation in sports and athletic scholarships, and residual functional impairments are difficult to calculate. ACL reconstructions using current methods do not fully restore normal knee kinematics, despite advanced surgical procedures and rehabilitation. In addition, the injury creates long-term changes in the biochemical environment of the knee joint, which is believed by some investigators to be a significant factor in the development of subsequent joint osteoarthritis [133, 134]. Authors have reported that 15–30% of patients who undergo ACL reconstruction will suffer a tear to either the reconstructed knee or contralateral knee upon return to sports activities, which may be due in part to inadequate postoperative rehabilitation and failure to include advanced neuromuscular retraining [135–139].

At present, there is no definitive test or set of tasks that depict athletes who may be at higher risk for a noncontact ACL injury. Although biomechanical risk profiles have been explored, studies have yet to determine if these profiles are directly linked to an increased risk for ACL injuries, and these studies involve sophisticated laboratory testing that is not available to most clinicians [140, 141]. Even so, many authors believe that neuromuscular retraining (as described in *Part III*) should become widespread to include all female athletes involved in high-risk sports such as basketball and soccer [108, 142–144]. Research has shown that comprehensive training programs can effectively "reprogram" the neuromuscular system to avoid potentially dangerous body mechanics and positions. Studies have proposed that these alterations in neuromuscular indices and movement patterns may reduce the incidence of noncontact ACL ruptures [106, 108, 143]. One investigation determined that universal neuromuscular training of all athletes is more cost-effective than no training (or screening) or training only athletes identified as high-risk for ACL injury [145]. Universal training was predicted to save $100 per player per season and would reduce the incidence of ACL injury from 3 to 1.1% per season. Systematic reviews have noted that, while some ACL injury prevention programs are effective in reducing the risk, others are not and it is crucial to understand why differences in outcomes have occurred [144, 146–151].

The American Academy of Pediatrics issued the following three-part policy statement in 2014 regarding ACL injury prevention training [6], which we agree with:

- Neuromuscular training appears to reduce the risk of injury in adolescent female athletes by 72%. Prevention training that incorporates plyometric and strengthening exercises, combined with feedback to athletes on proper technique, appears to be most effective.
- Pediatricians and orthopedic surgeons should direct patients at highest risk of ACL injuries (e.g., adolescent female athletes, patients with previous ACL injury, generalized ligamentous laxity, or family history of ACL injury) to appropriate resources to reduce their injury risk (http://www.aap.org/cosmf). Such discussions also should be appropriately documented in the patient's medical record.
- Pediatricians and orthopedic surgeons who work with schools and sports organizations are encouraged to educate athletes, parents, coaches, and sports administrators about the benefits of neuromuscular training in reducing ACL injuries and direct them to appropriate resources (http://www.aap.org/cosmf).

Critical Points

- What places female athletes in certain sports at a higher risk for ACL injuries than male athletes is unknown.
- Major risk categories: genetics, environmental, anatomical, hormonal, neuromuscular/biomechanical.
- Comprehensive training programs can effectively "reprogram" the neuromuscular system. However, not all published programs have significantly reduced the risk of injury.
- Alterations in neuromuscular indices and movement patterns have resulted in a reduction in the incidence of noncontact ACL ruptures.
- The American Academy of Pediatrics recommends neuromuscular training for female athletes and other high-risk individuals.

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2

Consequences of Complete ACL Ruptures

Sue Barber-Westin and Frank R. Noyes

Abstract

This chapter reviews the potential problems caused by ACL tears that are treated conservatively. A general consensus exists among clinicians that a complete ACL rupture causes long-term problems, especially a decrease in activity level and an early onset of knee osteoarthritis. Few patients sustain an isolated ACL tear as concomitant bone bruising has been documented in 80–95% of patients, meniscus tears occur in approximately 60%, and chondral injuries occur in 20%. Frequent subsequent reinjuries causing meniscus tears have been reported in the majority of studies, along with chondral damage and articular cartilage lesions that presumably result from traumatic giving-way episodes or increased catabolic activity. Knees with ACL deficiency that undergo meniscectomy have an increased risk of developing early arthritis compared with those that do not sustain meniscus damage. Altered knee kinematics, quadriceps weakness, and abnormal gait patterns that increase or alter joint loads and contact pressures may cause early arthritis in ACL-deficient knees.

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2.1 Introduction

Several long-term prospective studies have been published that described the natural history of complete anterior cruciate ligament (ACL) tears [1–11]. It is important to differentiate complete from partial ACL deficiency and to realize that some studies combine patients with these diagnoses into a single cohort, thereby precluding conclusions on the effects of a completely nonfunctional ligament. For the purpose of this chapter, complete ACL deficiency is defined as ≥5 mm of increased anterior tibial translation on an instrumented or clinical Lachman test (Fig. 2.1) and a fully positive pivot-shift test (grade 2 or 3 on a 0–3 point scale). The International Knee Documentation Committee (IKDC) ligament examination grade of C (abnormal) or D (severely abnormal) also identifies a complete ACL tear [12]. In contrast, patients with <5 mm of increased anterior tibial translation or a grade 1 pivot-shift test may have a partial ACL tear with some residual function remaining or may have an intact ACL with physiologic laxity. In some knees with a complete ACL tear, abnormally tight medial and lateral ligament restraints prevent a positive grade 2 pivot-shift test. This chapter focuses on the natural history of complete ACL deficiency, using data from investigations where documentation of the extent of the ACL injury was provided from either clinical examination, direct arthroscopic visualization,

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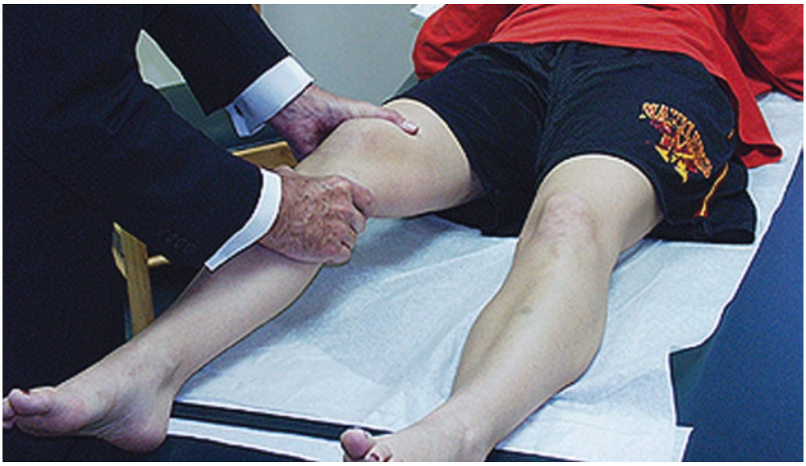

Fig. 2.1 Fully positive Lachman test (From Noyes FR, Barber-Westin SD (2017) Medial and posteromedial ligament injuries: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 608–635)

arthrometer testing, or a combination of these measures.

Studies vary with regard to the percentage of ACL-deficient patients who sustain repeat giving-way episodes, symptoms with athletic and daily activities, and alterations in muscle activation patterns and neuromuscular control [13–15]. Even so, the general consensus is that a complete ACL rupture causes both short- and long-term problems in the knee joint, including subsequent meniscus tears and the development of osteoarthritis (OA) (Fig. 2.2) [7, 13, 16–23]. In a cohort of 3475 patients with ACL injuries treated with reconstruction, Granan et al. [18] reported that the odds of an articular cartilage lesion in the skeletally mature knee increased by 1% each month that elapsed from the ACL injury to surgery. Roos et al. [24] reported that 564 patients with chronic, untreated ACL ruptures showed radiologic signs of OA (joint space narrowing) 10 years earlier than 401 patients with intact ACLs and chronic meniscus tears that had not been surgically addressed. Lohmander et al. [25] found that one-third of soccer players had joint space narrowing on radiographs 10 years after a combined ACL and meniscus injury, which increased to one-half of the players at 20 years. Noyes et al. [14] reported that 44% of 39 patients with chronic ACL ruptures of at least 5 years duration had moderate or severe radiographic osteoarthritic changes.

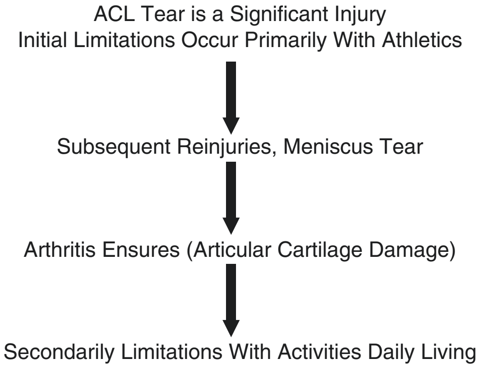

Fig. 2.2 Sequela of the majority of ACL ruptures treated conservatively

The identification of so-called copers, or patients with ACL-deficient knees who may be able to return to sports without undergoing early ACL reconstruction, has been the topic of interest of several studies [2, 11, 26–28]. Studies vary widely in the percentage of patients who fit this description. For instance, one study [26] found that only 5% of 42 subjects returned to high-demand athletics, and another study [11] reported that only 5% of 38 patients returned to high-risk pivoting sports. One investigation [2] reported that while 43% of 63 patients returned to high-level sports initially after their ACL injury, only 17% were still participating at final follow-up.

A significant problem is that few patients sustain an isolated ACL tear because 80–95% have bone bruising; 60%, meniscus tears; and 20%, chondral injuries [2, 29–33]. Further compounding the problem is the occurrence of subsequent meniscus tears that are reported in the majority of natural history studies [7, 10, 13, 17, 22, 34].

A meta-analysis that compared outcomes of 13 studies of ACL tears treated nonoperatively with 24 studies of ACL tears treated with reconstruction found that nonoperative treatment significantly increased the odds of subsequent meniscus surgery (effect size [ES] 1.87, $P < 0.01$) [13].

Substantial evidence exists that knees with ACL deficiency that undergo meniscectomy (Fig. 2.3) have an increased risk of developing early arthritis compared with those that do not sustain meniscus damage (see also Chap. 4) [7, 35, 36]. Knees with isolated ACL tears may experience a reduction in synovial fluid lubricin concentration and an increase in levels of inflammatory cytokines that may place the joint at increased risk for articular cartilage deterioration [37]. Knees with combined ACL tears and meniscus tears may exhibit a higher expression of catabolic markers compared with knees with isolated meniscus tears, which may lead to a higher risk for the development of OA [38].

Fig. 2.3 Anteroposterior radiograph of a chronic ACL-deficient knee that underwent a medial meniscectomy. The patient presented to our center 7 years later with medial tibiofemoral joint pain and required a high tibial osteotomy for varus malalignment

A cost analysis of ACL tears treated with reconstruction compared with structured rehabilitation revealed substantial savings in reconstructed knees for both short-to-intermediate term and lifetime costs (Table 2.1) [39]. For instance, the mean lifetime cost to society for a patient undergoing ACL reconstruction was calculated to be $38,121 (2012 US dollars) compared with $88,538 for a patient treated with just rehabilitation. The combined increase in quality of life and cost savings lead Mather et al. [39] to conclude that ACL reconstruction is the preferred cost-effective treatment strategy for ACL tears. However, the costs to society for all ACL tears, regardless of treatment, run in billions of dollars annually, and these authors recommended that resources be directed to develop innovations for injury prevention and for altering the natural history of this injury. The potential consequences of

Table 2.1 Costs of treating ACL injuries with reconstruction compared with structured rehabilitation[a]

Variable	ACL reconstruction	Structured rehabilitation
Short-intermediate (6 year fu) net societal savings	$4503	–
Long-term (≥ 10 year fu) net societal savings	$50,417	–
Lifetime cost per patient	$38,121	$88,538
Lifetime burden U.S. society (annual)	$7.6 billion	$17.7 billion
No. patients that will develop radiographic OA (lifetime)	118,000 (59%)	140,000 (70%)
No. patients that will develop symptoms	31,600 (16%)	38,000 (19%)
No. patients that will require total knee arthroplasty	25,800 (13%)	30,800 (15%)

[a] Data from Mather et al. [39], calculated according to annual incidence of 200,000 ACL tears in the USA

ACL tears treated conservatively are detailed next in this chapter.

Critical Points

- Few long-term prospective studies on natural history of the ACL-deficient knee.
- General consensus: ACL injury causes long-term problems and early onset of osteoarthritis compared to general population.
- Few patients sustain isolated ACL tear: 80–95% have bone bruising, 60% meniscus tears, 20% chondral injuries.
- Associated meniscus tears increased likelihood of development of osteoarthritis.

2.2 Consequences of ACL Deficiency

2.2.1 Alterations in Knee Kinematics

Different theories exist regarding the causes of the development of early OA in ACL-deficient knees, including altered knee kinematics that increase or alter joint loads and contact pressures from in vivo and in vitro studies [40–49]. Zhang et al. [49] measured the 6 degrees-of-freedom kinematics of ACL-deficient and contralateral normal knees in 56 patients during level treadmill walking using an optical tracking system. Fifteen patients had an isolated ACL injury, 15 had an associated medial meniscus tear, 15 had a lateral meniscus tear, and 11 had medial and lateral meniscus tears. All ACL-deficient knees had reduced knee flexion of approximately 6°–8° during the gait cycle (stance and swing phases, $P < 0.05$, Table 2.2). Knees with ACL deficiency and either medial or lateral meniscus tears had significantly greater anterior femoral translation of approximately 2.3–3.6 mm compared with intact knees in the majority of the swing phase ($P < 0.05$). However, knees with both medial and lateral meniscus tears showed reduced anterior femoral translation (mean 3 mm) compared with intact knees ($P = 0.008$). Other significant findings from this study are shown in Table 2.2. The authors concluded that meniscal injuries alter the kinematics of the ACL-deficient knee and that these alterations depend on the location (tibiofemoral compartment) of the meniscus tear.

Defrate et al. [50] and Van de Velde et al. [47] measured tibiofemoral kinematics during a

Table 2.2 Six degree-of-freedom kinematics of ACL-intact and ACL-deficient knees during treadmill walking[a]

Kinematic variable		ACL-deficient knees[b]			
	ACL-intact knees[b]	Isolated ACL tear	ACL + medial meniscus tear	ACL + lateral meniscus tear	ACL + medial and lateral meniscus tear
Rotation (°)					
Flexion (+)–extension	21.1 ± 20.3	17.9 ± 17.9[c]	17.0 ± 17.9[c]	17.4 ± 19.7[c]	12.7 ± 19.7[c,d,e,f]
Internal–external (+)	0.6 ± 4.7	2.0 ± 4.5[c]	1.8 ± 6.0	2.4 ± 5.7[c]	2.6 ± 2.6[c]
Translation (mm)					
Anterior (+)–posterior	4.3 ± 6.4	3.6 ± 6.4	7.9 ± 6.1[c,d]	6.6 ± 7.6[c,d]	1.3 ± 3.9[c,e,f]
Proximal (+)–distal	8.9 ± 5.0	7.9 ± 5.4	7.7 ± 6.1	7.8 ± 6.8	5.0 ± 5.9[c,d,e,f]
Medial–lateral (+)	−0.3 ± 4.5	0.1 ± 3.9	−2.9 ± 4.7[c,d]	−0.8 ± 4.3[e]	1.4 ± 3.6[c,e,f]

[a] Data from Zhang et al. [165], positional and orientational changes of the femur relative to the tibia. Data are reported as mean ± standard deviation

[b] Statistically significant difference ($P < 0.05$) compared with [c]ACL intact, [d]isolated ACL, [e]ACL + medial meniscus tear, [f]ACL + lateral meniscus tear. There were no significant findings for adduction-abduction

single-leg lunge with in vivo dual fluoroscopic imaging analysis in 10 ACL-deficient patients. Compared with the intact contralateral knee, small changes were noted in increased anterior tibial translation (approximately 3 mm) and internal tibial rotation (approximately 2°). Li et al. [51] reported that a shift occurred during a single-leg weight-bearing lunge in tibiofemoral contact points in both the anteroposterior and mediolateral directions in 9 ACL-deficient knees. The primary finding was a posterior shift of the tibiofemoral cartilage contact points in the medial tibiofemoral compartment near full extension. For example, at 0° extension, the mean contact point (medial tibiofemoral compartment) was 6.3 ± 1.8 mm anterior to the midline of the tibial plateau in intact knees compared with a mean contact point 2.1 ± 2.8 mm anterior to the midline in ACL-deficient knees ($P < 0.05$).

Nicholson et al. [43] used an upright, full weight-bearing MRI to compare kinematic findings in eight ACL-deficient knees compared with contralateral knees and five knees from healthy volunteers. Knees were scanned at 0°, 30°, 60°, and 90° of flexion. In the ACL-deficient knees, the medial tibial plateau was displaced anteriorly a mean of 2.2 mm from 0° to 60° flexion. The lateral tibial plateau subluxed anteriorly a mean of 4.9 mm from 0° to 60° flexion. The larger subluxation of the lateral tibial plateau was attributed to increased internal rotation; however, exact rotational data were not provided.

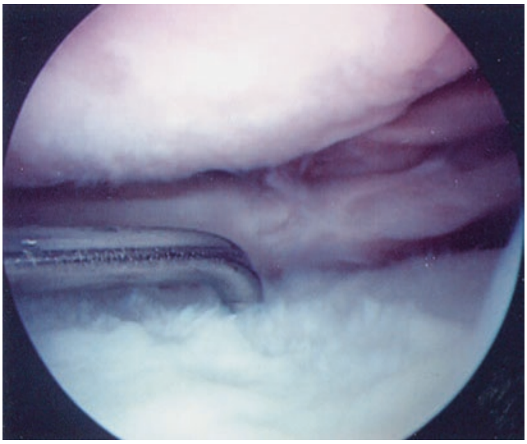

Fig. 2.4 A 21-year-old patient who underwent a lateral meniscectomy 2 years prior to presentation to our center. Diffuse articular cartilage damage is visible on both the lateral femoral condyle and lateral tibial plateau (From Noyes FR, Barber-Westin SD (2017) Meniscus transplantation: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 719–759)

In a review of multiple laboratory studies, Chaudhari et al. [41] hypothesized that changes in tibiofemoral knee motion after ACL injury during walking result in increased loading in areas of the articular cartilage not accustomed to such loads, in addition to reduced loading in areas normally conditioned to receive large loads (see also Chap. 8). These alterations were speculated to shift contact pressure distributions and induce cartilage deterioration (Fig. 2.4). Andriacchi et al. [52] created a finite-element model using three-dimensional cartilage volumes from MRI images to predict progression of OA in normal and ACL-deficient knees. A more rapid rate of cartilage thinning was predicted in the ACL-deficient knees, especially in the medial tibiofemoral compartment. The investigators concluded that this was due to a shift in the normal load-bearing regions of the knee joint during weight-bearing activities.

Logan et al. [53] measured tibiofemoral motion from 0° to 90° using an open, vertically oriented MRI under full weight-bearing conditions in ten patients who had isolated ACL ruptures. Anterior subluxation of the lateral tibial plateau occurred throughout the arc of motion compared with the contralateral normal knee. For instance, at 0° of knee extension, the distance from the center of the femoral condylar facet to the lateral posterior tibial cortex was 15.8 ± 2.9 mm in ACL-deficient knees compared with 21.4 ± 1.4 mm in normal knees ($P < 0.0001$). The authors concluded that this abnormal position may facilitate the pivot-shift phenomenon or giving-way during activity and may also account for degenerative changes following ACL injury. Other factors which may play a role in the development of OA in ACL-deficient knees include prolonged elevated cartilage biomarkers, genetic predisposition, weight gain, restricted physical activity, lower extremity malalignment (which may increase with age), chronic quadriceps weakness, and gait abnormalities [20, 36–38].

2.2.2 Articular Cartilage Lesions and Osseous Deficits

Chronic ACL deficiency may lead to full-thickness articular cartilage lesions [9, 18, 21, 23, 32, 54]. Rotterud et al. [23] determined the incidence and risk factors for full-thickness cartilage lesions in a cohort of 15,783 patients with ACL tears. Of these, 27% had partial-thickness cartilage lesions and 6.4% had full-thickness lesions. The odds of full-thickness lesions increased by 1.006 for each month that elapsed from the injury to surgery (in patients reconstructed >1 year since the injury) and increased by 1.05 for each year of increasing patient age.

A longitudinal assessment of femoral condyle articular cartilage quality was performed in 29 ACL-injured knees and 24 control healthy knees using contrast-enhanced MRI by Neuman et al. [54] The patients were scanned 3 weeks after their injury and a mean of 2.3 years later. Joint cartilage glycosaminoglycan (GAG) content was estimated using delayed gadolinium-enhanced MRI of cartilage (dGEMRIC). A shorter T1Gd value (dGEMRIC index) is consistent with low cartilage GAG content and is indicative of early-stage knee OA. The ACL-injured patients had shorter T1Gd values compared with control knees at both evaluations in both the medial compartment (363 ± 61 ms and 428 ± 38 ms, respectively, $P < 0.0001$) and in the lateral compartment (396 ± 48 and 445 ± 41 ms, respectively, $P < 0.001$). The ACL-injured patients who underwent meniscectomy had significantly shorter T1Gd values compared with patients with intact menisci.

Potter et al. [32] conducted longitudinal MRI with T2 mapping at baseline (<8 weeks after injury) and yearly for a maximum of 11 years in 42 knees that sustained acute isolated ACL tears. All knees demonstrated cartilage injury at baseline, most severely over the lateral tibial plateau and lateral femoral condyle. Fourteen knees were treated conservatively, and 28 underwent ACL reconstruction. At the latest follow-up, the conservatively treated group had statistically significant higher odds ratio (OR) for cartilage loss over the medial tibial plateau (OR 5.9, $P = 0.003$) and patella (OR 4.9, $P = 0.02$) compared with the surgical group. These investigators noted that even though the initial severe chondral injuries occurred in the lateral compartment, the rate of progression was highest in the medial and patellofemoral compartments, indicating the natural rate of chondral loss after ACL injury.

Nyland et al. [55] conducted a systematic literature review to determine the effect of ACL rupture on bone mineral density (BMD), bone content, and bone area mass. The study revealed that osseous deficits were detected within 1 month following the injury and persisted up to 20 years later. No study reported that BMD, bone area mass, or bone content returned to normal levels regardless of the treatment of the ACL rupture (nonoperative or operative). All studies used dual-energy X-ray absorptiometry (DEXA) to measure BMD. Reduced bone integrity was reported throughout the lower extremity, including the proximal tibia, distal femur, patella, proximal femur and hip, and calcaneus. The authors believed that trabecular cancellous bone loss was considerably higher than cortical bone loss. Significant associations were found between the time from injury and severity of bone loss [56, 57].

Bayar et al. [57] assessed BMD in 32 men with complete ACL ruptures. The mean time from injury to DEXA scanning was 24 months (range, 1–84). All patients had given up sports activities and complained of occasional giving-way. The results indicated significant BMD loss in the patella, medial tibial plateau, and lateral femoral condylar regions. A positive correlation was found between time from injury and BMD loss ($R^2 = 0.692$). The authors suggested that the osteoporosis in the patella in this group of patients may have been due to altered weight-bearing conditions and lack of use of the lower extremity, because all had quadriceps atrophy. Bone loss in the lateral femoral condyle was hypothesized to have been associated with possible bone bruising in that compartment, which is a common finding in acute ACL ruptures.

2.2.3 Biomarkers of Osteoarthritis

Recent studies have detected several biomarkers of inflammation and matrix degradation in ACL-deficient knees in both the acute-injury and long-term post-injury time periods [37, 58–65]. Two such markers are cartilage oligomeric matrix protein (COMP) and C-reactive protein (CRP), both of which have been used as diagnostic and prognostic indicators of OA. Palmieri-Smith et al. [66] studied 11 ACL-deficient knees with MRI-verified bone marrow edema lesions (100% on the lateral femoral condyle and 91% on the posterior lateral tibial plateau) and 11 control knees with no lesions to determine if differences existed in COMP and CRP levels. The ACL-deficient knees were tested a mean of 45 ± 14 days after the injury. COMP values were significantly higher in the ACL-deficient knees ($P < 0.05$, ES, 0.59). Neuman et al. [61] reported significantly increased concentrations of COMP and aggrecan ($P < 0.001$) in 88 patients tested within 2 weeks of sustaining ACL injuries compared with a control cohort.

Harkey et al. [59] conducted a systematic review of 20 studies that measured OA-related biomarkers after ACL injury and reconstruction. Synovial fluid levels of cartilage extracellular matrix degradation OA biomarkers were consistently increased after injury. The authors recommended the implementation of standardized reporting in future studies to determine which biomarkers are most indicative for the development of OA after ACL injury and reconstruction.

In a cohort of 38 patients followed a mean of 19.9 ± 2.6 years after ACL injury, Streich et al. [62] reported positive correlations with MRI-based volumetric cartilage measurements and cartilage biomarkers. C-terminal telopeptides of collagen type I (CTX-I) and collagen type II (CTX-II) are important risk factors for progression of OA. Levels of CTX-I were higher than normal and correlated with MRI volume and area of cartilage surface of the whole knee joint, as well as volume of cartilage on the tibia and femur of both tibiofemoral compartments. Levels of CTX-II were also higher than normal and correlated with area of subchondral bone eroded (full-thickness defect) on the medial tibia.

2.2.4 Chronic Muscle Weakness and Dysfunction

Chronic quadriceps weakness has been postulated as a risk factor for posttraumatic OA in the ACL-deficient knee [67]. The rationale stems from the resultant altered joint loads and failure to absorb energy adequately about the knee that place high dynamic forces on the articular cartilage, leading to its deterioration. Quadriceps muscular deficits have been reported by multiple investigations in ACL-deficient knees [68–75]. de Jong et al. [68] reported isokinetic quadriceps strength deficits of 17% at 60°/s and 12% at 180°/s in 191 patients a mean of 2.2 years after their ACL injury. Hsiao et al. [71] measured isometric and isokinetic muscle strength in 12 patients a mean of 18.5 months after ACL injury and a control cohort of 15 healthy adults at multiple knee flexion angles (10° to 90°) and testing velocities (50°/s to 250°/s). The ACL-deficient knees showed significant weakness in both quadriceps and hamstring muscles across the entire range of knee flexion angles and all test velocities ($P < 0.05$ to $P < 0.001$) compared with the contralateral knees. Eitzen et al. [69] reported significant differences between 44 subjects classified as potential copers and 32 patients deemed noncopers in quadriceps isokinetic torque (60°/s) at knee flexion angles of 15°–80° (with the exception of 50°; $P < 0.05$). For all patients, the largest strength deficits were found at flexion angles less than 40°.

Arthrogenic muscle inhibition (AMI) has been hypothesized by some investigators to cause acute and chronic quadriceps weakness in ACL-deficient knees [67, 70]. Authors have speculated that AMI occurs after this injury due to altered afferent feedback that results from damage to the knee joint and ACL mechanoreceptors, pain, and knee joint effusion. This condition prevents full voluntary muscle activation (essentially shutting the muscle down even though it is not damaged) as a natural response to protect the joint from further damage. However, AMI continues over time, resulting in chronic quadriceps weakness. The persistent muscle atrophy is postulated to be a factor in altered neuromuscular control during dynamic activities. Hart et al. [70] summarized ten studies with a total of 352 ACL-deficient knees that underwent measurement of quadriceps activation using force-based measurements. These include the superimposed burst technique (SIB) and the interpolated twitch technique (ITT), both of which use a supramaximal, percutaneous electrical contraction to calculate the central activation ratio. If a portion of the quadriceps is inhibited, the external stimulation will cause a force-producing contraction that is greater than the volitional contraction. A value >95% is considered normal, with all motor units in the quadriceps able to contract. Hart et al. [70] reported abnormal quadriceps activation from either SIB or ITT in 57% of the ACL-deficient knees, 34% of the uninvolved knees, and bilaterally in 21%. Unfortunately, confounding factors such as time from injury and patient activity levels at the time of testing could not be accounted for in this review.

Modern studies vary in regard to hamstring weakness in ACL-deficient knees [68, 73–75]. de Jong et al. [68] reported minimal isokinetic hamstring strength deficits (5% at 60°/s and 4% at 180°/s) in 191 patients a mean of 2.2 years after their ACL injury. Thomas et al. [74] reported a mean 30% deficit in hamstring isokinetic strength in 15 patients a mean of 69 days after ACL injury. Tsepis et al. [75] reported that poor hamstring strength was associated with low knee function with daily activities in a group of 32 male soccer players. The players were tested a mean of 32 months after their ACL injury. Patients with poor Lysholm scores had significantly lower average peak torque in the ACL-deficient knee compared with the opposite knee ($P < 0.001$), whereas patients with Lysholm scores >84 points had equivalent strength bilaterally.

2.2.5 Gait Abnormalities

Patients with ACL deficiency may demonstrate marked alterations in muscle activation patterns, knee moments, and knee kinematics during gait [45, 52, 76–87]. Studies have shown marked differences in gait abnormalities between patients who compensate well and do not experience instability (copers) and those who do not (noncopers) [76, 88, 92]. In one study [88], noncopers reduced their knee extensor moment and had smaller knee flexion angles compared with copers during the stance phase of walking. The walking pattern of copers resembled a hamstring facilitation pattern, as in that observed by Boerboom et al. [89]. Alkjaer et al. [76] revealed that noncopers walked with reduced knee compression and shear forces compared with control subjects, thereby reducing overall knee joint loading. Copers walked with the same amount of knee compression as control subjects; however, they reduced the anterior shear force applied to the tibia during the first half of the stance phase. Copers also demonstrated increased knee flexion angles during stance compared with noncopers and controls. The authors concluded the strategy adopted by the copers was more efficient to stabilize the knee joint during walking.

The quadriceps avoidance gait pattern has been identified in ACL-deficient knees in several investigations including 16 of 32 (50%) knees (that also had varus malalignment) in the authors' laboratory [84] and 12 of 16 (75%) subjects in a study by Berchuck et al. [90]. A systematic review [86] of 13 studies that used electromyography (EMG) to determine the incidence of this gait pattern found decreased quadriceps muscle activity in the acute stage after ACL injury and in noncopers patients. Altered quadriceps activity was not uniformly reported in ACL-deficient copers. Elevated or prolonged duration of hamstring activity was reported in noncopers and in both acute and chronic ACL-deficient knees. An overall increase in both quadriceps and hamstring activity, termed a *stiffening strategy*, was detected in noncopers with chronic ACL deficiency. Andriacchi and Scanlan [91] hypothesized that the reduction in quadriceps strength following ACL rupture could be explained in part by the reduction of the moment sustained by the quadriceps during walking.

Fuentes et al. [79] described a pivot-shift avoidance gait adaptation in chronic ACL-deficient knees, characterized by a significantly reduced internal rotation knee joint moment and a higher knee flexion angle during the terminal stance of the gait cycle. Twenty-nine patients underwent gait analysis using normal and fast walking speeds a mean of 22 months following their ACL injury, and the results were compared with a group of 15 healthy subjects. The ACL-deficient patients had significantly smaller internal rotation moments and significantly higher knee flexion angles than the control group ($P < 0.05$). The authors concluded that the ACL-deficient patients adopted this strategy to avoid placing their knee in a position that could lead to anterolateral rotatory knee instability during the terminal stance phase.

During the loading phase of level walking, ACL-deficient subjects have significantly decreased external knee flexion moments and increased external knee extension moments compared with uninjured control subjects (Fig. 2.5) [92]. Patel et al. [93] reported that patients with ACL deficiency had a significantly reduced peak external flexion moment during jogging and stair climbing which correlated with reduced quadriceps strength. Berchuck et al. [90] reported that the magnitude of the maximum knee flexion moment was reduced the most during walking, more so than during jogging (140% and 30%, respectively). Reduction of the flexion moment reduced quadriceps contractions and was related to the angle of knee flexion during each activity. These authors found gait adaptations in both the injured and contralateral limbs that were believed due to the symmetrical function required for weight-bearing activities.

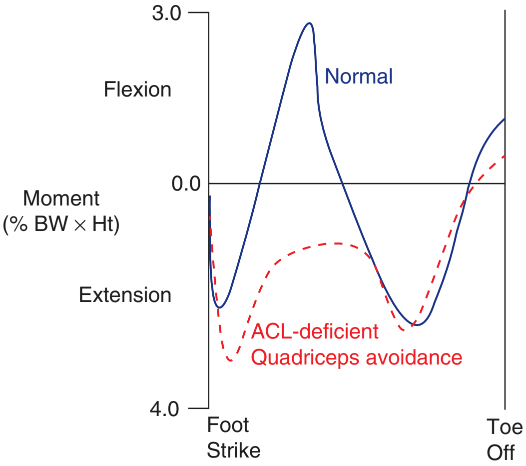

Fig. 2.5 The normal pattern of flexion-extension moment at the knee during the stance phase of gait (blue line) and the pattern of quadriceps avoidance as described by Berchuck et al. [90] in some ACL-deficient subjects

Many investigations have shown significant differences between ACL-deficient knees and controls on knee kinematics such as anteroposterior translation and internal-external tibial rotation during gait. For instance, Shabani et al. [45] found that ACL-deficient patients had significantly greater knee flexion during the stance phase of normal speed walking compared with a control group (13.2° ± 2.1° and 7.3° ± 2.7°, respectively, $P < 0.05$), as well as increased tibial internal rotation (−1.4° ± 0.2° and 0.2° ± 0.3°, respectively, $P < 0.05$). Chen et al. [78] also reported ACL-deficient knees had greater knee flexion during the stance phase of gait than the contralateral side (end of stance phase, 39.2° ± 13.1° and 34.8° ± 10.4°, respectively, $P < 0.05$). Zabala et al. [87] determined that the amount of time that elapsed since the ACL injury was an important factor in altered kinematics. In a study of 19 ACL-deficient knees with no signs of knee OA (time from injury, 1–384 months), a significant correlation was found between time from injury and side-to-side differences in anterior femoral rotation and external femoral translation. Knees designated as long-term (>1 year post-injury) had significantly greater values for anterior femoral translation ($P = 0.01$) and external rotation ($P = 0.004$) compared with knees with short-term follow-up.

2.2.6 Changes in Muscle Activation Strategies During Functional Activities

Patients with ACL-deficient knees commonly demonstrate different lower extremity dynamic muscle activation patterns compared with healthy controls during functional activities. These altered muscle activity strategies are presumed to be related to the attempt to prevent anterior tibial translation and internal tibial rotation through either increased hamstring activity or decreased quadriceps activity, depending on the task.

Alkjaer et al. [94] recorded EMG and net knee joint moments during maximal isokinetic concentric quadriceps and eccentric hamstring contractions at 30°/s in a cohort of seven male subjects with chronic ACL deficiency. Compared with a control group, the magnitude of hamstring EMG was 65% higher in the ACL-deficient knees between 20° and 80° of flexion ($P < 0.05$). The hamstring moment, expressed in percentage of the measured net extension moment, was elevated in ACL-deficient knees compared with controls at 20° to 50° of flexion ($P < 0.05$). The marked increase in hamstring contraction toward knee extension most likely reflected a compensation strategy to provide stability to the knee.

Roos et al. [95] studied muscle control strategies during a double-legged squat in 20 patients with chronic ACL-deficient knees. Compared with a control group, the patients had a significant reduction in squat depth (113° ± 21° and 105° ± 21°, respectively, $P < 0.001$) and used compensation mechanics that lowered the loading on their injured limb. The peak knee extensor moments in the patients were significantly lower in both the injured and contralateral sides ($P < 0.001$). The authors termed these differences in mechanics as an *avoidance strategy*, which correlated with poorer quadriceps and hamstring isokinetic strength and increased fear of reinjury.

Oberlander et al. [96] examined joint kinetics and dynamic stability control on landing after a single-leg hop test in 12 ACL-deficient patients. The goal was to determine the interaction between trunk angle characteristics, knee joint kinetics, and dynamic stability control. The ACL-deficient patients demonstrated lower external knee flexion moments compared with their contralateral limb and that of healthy subjects ($P < 0.05$) and also had higher moments at the ankle and hip joints. The position of the center of mass on landing was significantly more anterior for the ACL-deficient leg compared with the contralateral side ($P < 0.01$), and the trunk angle was more flexed at the ACL-deficient leg ($P < 0.01$). The authors postulated that this altered motor strategy, a more anterior position of the whole body center of mass, diminished the ability to control dynamic stability and could increase the risk for falls.

Phillips et al. [97] assessed the effectiveness of landing strategies in 30 ACL-deficient subjects compared with 30 controls using dynamic balance measures. The ACL-deficient patients required more time to decelerate on landing from a hop and during a run and stop maneuver ($P < 0.05$). They also required a greater amount of time to regain stability on landing ($P < 0.01$) and failed a significantly greater number of landing attempts.

Williams et al. [98] examined the volume and cross-sectional area of the quadriceps, hamstrings, and gastrocnemius using MRI and voluntary muscle control with surface EMG of 18 patients with chronic ACL-deficient knees. Nine subjects were classified as copers and nine as noncopers. Significant atrophy of the quadriceps muscles (4.5–13% lower muscle volume) was observed in the noncopers compared with the contralateral limb, those of the copers, and a control group. This group had diminished volume and control in the vastus lateralis on the injured side and "fired their quadriceps in circumstances in which muscle activity was atypical and seemingly counterproductive" [98]. The copers' quadriceps were not atrophied, and their vastus lateralis muscles were significantly larger on their involved side (8% greater volume) compared with the contralateral side. The study did not evaluate isokinetic muscle strength indices.

2.2.7 Alterations in Proprioception and Balance

The ACL and knee joint capsule contain mechanoreceptors which provide information regarding joint position to the central nervous system for communication with muscles to provide dynamic protection to the joint [99]. These include Ruffini endings, Pacinian corpuscles, and Golgi tendon organs. This proprioceptive behavior has been defined in terms of static awareness of joint position in space, kinesthetic awareness (detection of limb movement and acceleration), and closed-loop afferent activity required for a reflex response and the regulation of muscle stiffness [100, 101].

The most common tests for proprioception are joint kinesthesia (threshold to detect passive motion [TDPM]) and joint position sense (JPS). There exists evidence that some patients may experience altered proprioception [102–104] and balance control [97, 105–110] following ACL injury. Control of posture and balance, either static or dynamic, is dependent on sensory information gained from proprioception and the vestibular and visual systems. Impairment of any of these factors may affect postural control.

Adachi et al. [111] examined the remnants of ruptured ACLs in 29 knees removed arthroscopically. The mean interval from injury to surgery was 8 months (range, 2 months to 10 years). In all, the ACL remnant was still attached to the femur and tibia. Mechanoreceptors were found in all knees and ranged in number from 8 to 30. JPS testing before surgery found a small but significant difference in the mean inaccuracy to determine joint position sense (median difference, 1.3°, $P < 0.001$). There was an inverse correlation between the number of mechanoreceptors and the final inaccuracy of joint position sense ($R = -0.41$, $P = 0.03$). Katayama et al. [112] measured JPS in 32 chronic ACL-deficient knees and found significant differences between the injured and contralateral limbs (5.2° and 3.6°, respectively, $P < 0.05$). Relph and Herrington [103] measured JPS of 20 chronic ACL-deficient patients and 20 matched controls from 0° to 30° of flexion in which knee angles were measured with two-dimensional digitizing software. The ACL-deficient knees had significantly greater mean error scores compared with the contralateral leg (7.9° ± 3.6° and 2.0° ± 1.6°, respectively, $P < 0.001$, ES 0.61) and the control group (2.6° ± 0.9°, $P < 0.001$, ES 0.77).

A review of 24 studies was conducted by Gokeler et al. [113] to determine the clinical relevance of proprioceptive deficits in ACL-deficient knees and ACL-reconstructed knees. The mean angles of error for TDPM and JPS were 0.4° and 0.8°, respectively, in the ACL-deficient knees; 0.2° and 0.5°, respectively, in ACL-reconstructed knees; and 0.1° and 0.1°, respectively, in healthy control subjects. The authors concluded that these very small differences were most likely not clinically relevant.

Proprioception of both knees during non-weight-bearing (JPS and TDPM) and full weight-bearing, as well as postural sway, was measured in 25 patients with chronic ACL-deficient knees and 25 controls [105]. The mean error in JPS was significantly greater in both knees in the ACL-injured patients compared with controls ($P < 0.001$); however, the mean differences were ≤2°. For instance, at 30° of flexion, the mean JPS deficits for the ACL-injured knees, the contralateral knees, and the control knees were 4.4° ± 1.2°, 4.1° ± 0.7°, and 2.4° ± 0.3°, respectively.

The influence of anterior tibial translation, muscle peak torque, and proprioception on dynamic balance was measured in a group of 12 chronic ACL-deficient subjects by Lee et al. [110]. Significant differences were found between limbs in TDPM, hamstring strength, quadriceps strength, and postural sway (Table 2.3,

Table 2.3 Knee laxity, proprioception, muscle strength, and dynamic standing balance values in ten young men with chronic ACL injuries[a]

Variable	ACL-deficient side	Contralateral side	*P* value
Anterior tibial displacement (148 N, mm)	11.8 ± 2.1	4.7 ± 1.6	<0.001
Passive repositioning test (°)	4.64 ± 1.7	3.53 ± 1.3	0.001
Threshold for detection of passive motion (°)	3.76 ± 2.6	2.61 ± 1.95	0.02
Quadriceps strength (60°/s, Nm)	121 ± 32	156 ± 39	<0.001
Hamstring strength (60°/s, Nm)	99 ± 22	123 ± 29	<0.001
Hamstring/quadriceps ratio	83 ± 10	79 ± 10	NS
Tilt angle of balance (°)	6.68 ± 2.28	5.41 ± 1.92	<0.001

[a] Data from Lee et al. [110]

NS not significant

$P < 0.01$). A correlation was found between TDPM and balance, with poorer proprioception resulting in poorer dynamic static balance in the ACL-deficient knee. Park et al. [114] reported significant correlations between isokinetic extensor and flexor strength and single-leg balance stability (60°/s; R −0.52 and −0.51, respectively, $P = 0.01$), with greater muscle strength associated with improved stability.

The effect of perturbation on standing balance was assessed in 12 chronic ACL-deficient knees by Ihara et al. [109]. Postural control functions that were observed in uninjured subjects, including supporting the body on the side of the balance board that was tilted and preventing loss of balance, were not present in the ACL-deficient subjects. Both the injured and uninjured sides were impaired.

Herrington et al. [108] found significant differences between 25 patients with chronic ACL deficiency and 25 uninjured subjects in dynamic postural control while balancing on a single limb and moving the other limb in specific directions. The patients had deficiencies in both the injured and uninjured sides. Arockiaraj et al. [105] reported significant higher postural sway in 25 ACL-deficient knees compared with 25 controls during a single-leg 10-s test.

2.2.8 Impairment in Single-Leg Hop Functional Testing

Noyes et al. [115] conducted four single-leg hop tests (single hop [Fig. 2.6], timed hop, triple hop, and triple crossover hop) in 67 patients with chronic ACL deficiency. When the data of only one test was considered, 49–52% had abnormal lower limb symmetry (defined as <85% difference between sides). When the results of two tests combined were analyzed, 62% had abnormal symmetry. An association was found between abnormal lower limb symmetry and quadriceps isokinetic peak torque ($R = 0.49$, $P < 0.01$).

Bryant et al. [116] found significant correlations between isokinetic peak flexion torque (180°/s) and single-leg hop performance in 13 ACL-deficient patients ($P = 0.02$). Wilk et al. [117] reported, in 50 patients with chronic ACL deficiency, that 47% had abnormal limb symmetry on the single-leg hop and 44% on the triple crossover hop. A correlation was found between these hop tests and knee extension peak torque at 180°/s ($R = 0.60$–0.69; $P = 0.05$–0.001) and at 300°/s ($R = 0.48$–0.64; $P = 0.01$–0.001).

Fig. 2.6 The single-leg hop test

Five single-leg hop tests (single hop, vertical jump, square hop, side hop, drop jump followed by a double hop for distance) were evaluated by Gustavsson et al. [118] in 30 patients with ACL-deficient knees. A significant difference was found between the injured and contralateral side for all of the tests except the square hop ($P < 0.05$). There were significantly larger side-to-side differences in the ACL-deficient patients compared with the controls ($P < 0.01$).

Critical Points

- Altered knee and lower limb kinematics that increase or alter joint loads and contact pressures may cause early OA in ACL-deficient knees.
- Prolonged elevated biomarkers of inflammation and matrix degradation, genetic predisposition, weight gain, restricted physical activity, lower extremity malalignment, chronic quadriceps weakness, and gait abnormalities may also contribute to early OA.

- Chronic ACL deficiency may lead to full-thickness articular cartilage lesions, especially with loss of meniscus.
- Patients with ACL deficiency may demonstrate marked alterations in muscle activation patterns, knee moments, and knee kinematics during gait.
- There exist marked differences in gait abnormalities between copers and noncopers.
- Chronic ACL deficiency may lead to different lower extremity dynamic muscle activation patterns in order to prevent anterior tibial translation and internal tibial rotation compared with healthy controls during functional activities.
- ACL-deficient knees may experience altered proprioception, but the clinical significance of the small deficits remains unclear.
- ≥50% of ACL-deficient knees have poor limb symmetry on single-leg hop tests.

2.3 Added Problems with Loss of Meniscus Function

2.3.1 Review of Biomechanics and Function of the Menisci

The menisci provide several vital mechanical functions in the knee joint, and loss of these structures leads to instability, symptoms of pain and swelling, loss of tibiofemoral joint space, and articular cartilage degeneration [7, 35, 36, 119–122]. 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.

Under weight-bearing conditions, the menisci assume a significant load-bearing function in the tibiofemoral joint [123–125]. At least 50% of the compressive load of the knee is transmitted through the menisci at 0° of extension, and approximately 85% of the load is transmitted at 90° of flexion [123, 133]. The presence of intact menisci increases the contact area to 2.5 times the size compared with a meniscectomized joint [126]. 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 350% [125, 127].

The menisci remain in constant congruity to the tibial and femoral articular surfaces throughout knee motion [128, 129] and are believed to contribute to knee joint stability [130, 131]. 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 [132]. Recent studies indicate that the lateral meniscus may be more important than the medial meniscus in resisting anterior tibial translation during the pivot-shift test [131]. Total lateral meniscectomy results in a 50% decrease in total contact area and a 235–335% increase in peak local contact pressure [133].

Medial meniscectomy performed after sectioning of the ACL results in increased anterior translation at 20° of flexion compared with knees with intact ACLs [131, 134, 135]. The loss of the medial meniscus after an ACL injury is problematic, especially in varus-angulated knees (Figs. 2.7 and 2.8). In knees with posterior cruciate ligament (PCL) ruptures, the increase in posterior tibial translation allows a change in tibiofemoral contact where the meniscus posterior horns have a reduced weight-bearing function. This is sometimes referred to as a *PCL meniscectomy*. The effect is greater for the medial compartment where the middle and anterior thirds of the medial meniscus have less weight-bearing function compared with the lateral meniscus.

The loss of the medial meniscus results in a smaller, more medial displacement of the center of pressure. Load is subsequently transmitted through the articular cartilage and subchondral bone to the underlying cancellous bone through this more central route, thus stress-shielding the proximal aspects of the medial tibial cortex. The deleterious effects of meniscectomy on tibiofemoral compartment articular cartilage have been demonstrated in multiple studies [125, 126, 136, 137].

Fig. 2.7 Bilateral varus malalignment

2.3.2 Effects of Meniscectomy in Chronic ACL-Deficient Knees

Approximately one-half of patients that sustain injuries to the ACL also suffer meniscus tears [4, 9, 21, 122, 138–142]. Most studies report a higher incidence of lateral meniscus tears than medial meniscus tears in acute ACL-injured knees [21]. However, if the injury is treated conservatively, a higher incidence of secondary medial meniscus tears has been noted [21, 143–145]. For instance, in a series of 1192 patients who underwent ACL reconstruction for acute (853 patients) or chronic (339 patients) (>6 months from injury) ruptures, Nguyen et al. [21] reported that the chronic subgroup had significantly more medial meniscus tears than the acute subgroup (49% and 22.5%, respectively, $P < 0.001$) and more articular cartilage injuries (54% and 33%, respectively, $P < 0.001$). Kennedy et al. [143] reported that

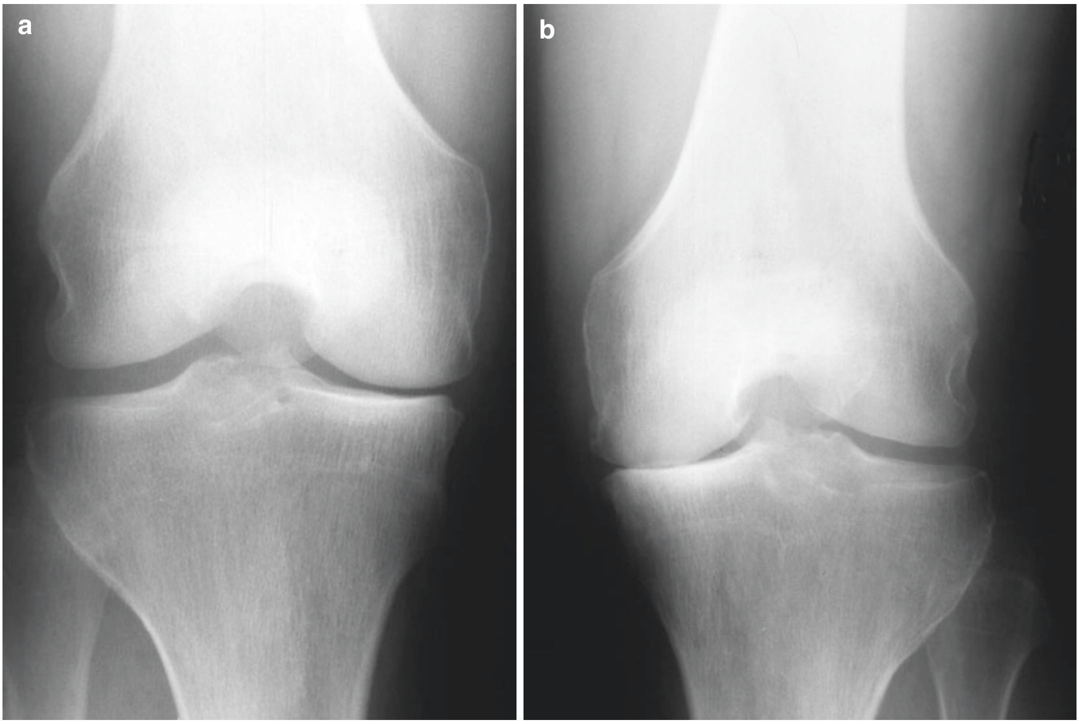

Fig. 2.8 Anteroposterior radiographs of the right (**a**) and the left (**b**) knees in a 45-year-old retired professional football player. The advanced medial tibiofemoral compartment arthritis and loss of joint space were due to bilateral varus malalignment, medial meniscectomies, and the patient's body weight of 260 pounds (From Noyes FR, Barber-Westin SD (2017) Tibial and femoral osteotomy for varus and valgus knee syndromes: diagnosis, osteotomy techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 773–847)

patients had a significantly higher chance of sustaining a medial meniscus tear if 1 year had elapsed from their injury (OR 7.99, $P = 0.004$). In their cohort of 300 athletic patients, a significantly higher incidence of degenerative changes was found in knees that were greater than 6 months post-injury (OR 4.04, $P = 0.005$).

Murrell et al. [146] documented meniscal and articular cartilage damage in a series of 130 patients who presented for ACL reconstruction. Patients who had undergone meniscectomy and in whom the injury had occurred ≥2 years at the time of the examination had 18 times the amount of articular cartilage damage compared with those who had intact menisci and whose injury occurred within 1 month of the examination. In a series of 2616 patients aged 17–40 years, Granan et al. [18] found that the odds for sustaining a cartilage injury increased by 1% for each month that elapsed from the date of injury until ACL reconstruction. Cartilage lesions were noted to occur nearly twice as frequently if there was an associated meniscus tear.

Sanders et al. [9] followed 364 patients with ACL tears and an age- and gender-matched control group a mean of 14 years to determine the incidence of subsequent meniscus injury, OA, and total knee arthroplasty (TKA). Patients treated nonoperatively had a significantly higher risk of secondary meniscus tears (hazard ratio [HR] 18.0), OA (HR 14.2), and TKA (HR 4.0) than subjects without ACL tears. In addition, patients who required meniscectomy after the ACL injury had an increased risk of sustaining subsequent meniscus tears (HR 51.5).

Knees with chronic ACL deficiency that undergo meniscectomy have an increased risk of developing early OA compared with those that do not sustain meniscus damage [4, 7, 18, 36, 122]. Meunier et al. [122] followed 36 patients with untreated ACL tears for 14–19 years. Standing radiographs were classified for OA according to the Ahlback and Fairbank classification systems. Of the 22 knees with intact menisci, radiographic OA (grades 1–3) was noted in 7 (32%). Of the 14 knees that underwent meniscectomy, OA was detected in 10 (71%). In a series of meniscectomized knees, Burks et al. [147] reported poorer radiographic and clinical results in 35 patients who had chronic ACL-deficient knees compared with 111 patients who had ACL-intact knees. The patients were evaluated 13.8–16.4 years after meniscectomy.

Critical Points

- Menisci act as spacers between the femoral condyles and tibial plateaus, have significant load-bearing function in the tibiofemoral joint, increase contact area, and contribute to knee joint stability.
- Concomitant meniscus tears with acute ACL ruptures occur in approximately 50%.
- Overall incidence meniscus tears increases with time in chronic ACL-deficient knees.
- Knees with chronic ACL deficiency that undergo meniscectomy have an increased risk of early osteoarthritis compared with knees with intact menisci.

2.4 Effect of Nonoperative Treatment on Future Activity Levels and Symptoms

Investigators have reported a substantial decline in athletic participation and performance and an increase in symptoms in ACL-deficient knees, which only becomes more prominent with the passage of time from the original injury [3–5, 13, 148–152]. The classic study from Noyes et al. [14, 153] examined a group of 103 chronic ACL-deficient knees (mean age, 26 years) a mean of 5.5 years after their original injury. Seventy-six patients presented for treatment due to symptoms or a reinjury; none had other ligament ruptures or prior ligament surgery, although 51 had undergone a meniscectomy. Following the initial knee injury, 82% of the patients returned to sports. However, 5 years later, only 33% were still participating and had frequent symptoms. A giving-way reinjury had occurred in 51% within 1 year and in 64% within 2 years after the original injury. Swelling increased with time, as 9% had swelling with sports an average of 2 years after the injury, compared with 34% an average of 11 years after the injury ($P < 0.01$). A subgroup of 84 of these knees underwent a rehabilitation program and counseling and were followed a mean of 9 years from the original injury. From this cohort, Noyes devised the “rule of thirds” after noting that 32% had no change in their symptoms (which were aggravating), 36% had improved with treatment and considered their knee condition livable for daily activities, and 32% failed the program. Of those that failed, 9 patients had worsening of their symptoms, and 18 underwent ACL reconstruction.

Mihelic et al. [4] compared the results of 33 patients who underwent ACL reconstruction with those of 18 patients treated nonoperatively, all of whom were followed for 17–20 years. Significant differences were found in IKDC scores, the Lysholm score, and radiographic evidence of severe OA (Table 2.4).

In a systematic review of 29 studies involving 1585 patients followed a mean of 13.9 years after either ACL reconstruction or nonoperative treatment, Chalmers et al. [13] noted that nonoperative treatment resulted in a higher incidence of subsequent meniscal surgery (29.4% and 13.9%, respectively, $P = 0.002$) and a significant decline in the Tegner activity score (−3.1 and −1.9 points, respectively, $P = 0.02$).

Kostogiannis et al. [3] followed 100 patients prospectively 15 years after an acute complete ACL rupture. Twenty-seven patients were excluded due to subsequent surgery for either meniscus injuries or ACL reconstruction and 6 were lost to follow-up, leaving 67 patients with unilateral non-reconstructed ACL tears. At follow-up, 13 of these 67 patients (19%) had required arthroscopy due to knee symptoms. The mean scores for knee function deteriorated over time. Symptoms with daily activities were present in 22%. When compared with a control group, the patients scored significantly lower on the Knee Injury and Osteoarthritis Outcome Score subscales for symptoms, daily activities, sports and recreation function, and knee-related quality of life ($P < 0.01$).

Nebelung and Wuschech [5] prospectively followed a group of 19 high-level (Olympic) athletes who were 19–30 years old for 35 years following their ACL injury. None of the athletes underwent late ACL reconstruction. While all were initially able to return to training for their sport, all had retired 1–4 years later as professional athletes due to their knee problems. Ten years later, 15 (79%) had undergone meniscectomy. At the 20-year follow-up, all but one had severe arthritis symptoms and instability, and ten eventually required total knee replacement.

Critical Points

- Decline in athletic participation and performance, increase in symptoms in majority of ACL-deficient knees, becomes more prominent with time.
- Increasing number of poor results in ACL-deficient patients followed ≥4 years after injury. Poor prognostic indicators: significant pivot-shift, persistent quadriceps or hamstring strength deficits, repeat injuries, and repeat arthroscopy.
- 49 patients followed mean 8.0 ± 2.3 years post-injury: 80% decreased activity level because of knee symptoms, and 40% had multiple giving-way reinjuries.

Table 2.4 Comparison of nonoperative and operative treatment of ACL injuries in 54 patients 17–20 years later[a]

Variable	Nonoperative cohort (N = 36)	Reconstructed cohort (N = 18)	*P* value
Anterior drawer, normal/nearly normal	16%	72%	NA
Instability experienced with sports or heavy labor	100%	17%	NA
Overall IKDC score normal/nearly normal	16%	94%	NA
Subjective IKDC mean score	65	83	<0.05
Lysholm mean score	53	84	<0.05
IKDC radiographic grade severely abnormal	56%	16.5%	<0.05

[a]Data from Mihelic et al. [4]

IKDC International Knee Documentation Committee, *NA* not available

- 40 patients followed 3.7 years post-injury: 10% resumed preinjury sports without problems, and 90% had giving-way reinjuries.

2.5 Effect of Nonoperative or Delayed Operative Treatment in Skeletally Immature Athletes

The number of complete ACL ruptures in skeletally immature patients continues to rise with increased participation in sports activity and improved diagnostic skills in detecting these injuries. The management of midsubstance ACL injuries in this population is controversial, and the decision of choosing conservative treatment until skeletal maturity is reached versus early reconstruction is a multifactorial one. We agree with recent literature that recommends early operative correction of ACL ruptures in athletes to avoid subsequent reinjuries, meniscus injuries, and articular cartilage damage in the appropriately indicated patient [154–162]. However, many parents and patients choose conservative management, at least initially, in order to avoid the potential complications of leg-length differences, graft ruptures, and difficulty with rehabilitation. Prepubescent and some adolescent patients who sustain a midsubstance ACL rupture may not have the maturity or emotional ability to handle the rigors of surgery that includes graft harvest and prolonged rehabilitation.

Unfortunately, conservative management has a documented high rate of subsequent meniscus tears and chondral damage in skeletally immature patients [157, 159, 163, 164]. A systematic review performed by Vavken et al. [162] of 12 studies involving 476 patients reported that conservative management resulted in high proportions of complaints of instability, meniscal tears, and cartilage defects that required eventual surgical stabilization in an average of 50% of the subjects. A meta-analysis conducted by Ramski et al. [161] reported that patients treated conservatively were over 12 times more likely to have a medial meniscus tear compared with patients who underwent ACL reconstruction (35% and 4%, respectively, $P = 0.02$). Patients treated conservatively were 33.7 times more likely to have symptomatic instability than patients who underwent early ACL reconstruction ($P < 0.01$).

Anderson et al. [163] analyzed the correlation of timing of ACL surgery with meniscal and chondral damage in 135 knees. Risk factors for both meniscus tears and articular cartilage damage included increased time to surgery and any instability episode. Patients that had just one episode of instability had threefold higher odds of sustaining a high-grade lateral meniscus tear.

Lawrence et al. [159] followed 70 patients who sustained complete ACL ruptures before 14 years of age, 41 of whom underwent reconstruction <12 weeks after the injury and 29 of whom had surgery >12 weeks post-injury. The odds of sustaining an associated medial meniscus tear were four times greater in the delayed surgical group ($P = 0.04$), which increased to 11-fold higher if a subjective sense of instability was noted ($P = 0.03$). The odds of developing lateral condylar articular cartilage lesions were increased 11-fold in the delayed reconstruction group ($P = 0.002$), while the odds of developing patellofemoral chondral lesions were increased threefold ($P = 0.04$).

There is little doubt that this injury in very young, skeletally immature athletes has the same severity in terms of associated injuries and future injuries (if managed conservatively) as those documented in adult populations. The need for injury prevention training is apparent in younger athletes.

Critical Points

- Treatment recommendation of midsubstance ACL injuries in skeletally immature athletes is early surgical stabilization to avoid subsequent reinjuries, meniscus injuries, and articular cartilage damage.
- However, some of these patients may not have the maturity or emotional ability to handle the rigors of surgery and prolonged rehabilitation.
- Conservative management has a documented high rate of subsequent meniscus tears and chondral damage.

Conclusions

There is evidence that patients who are willing to significantly modify athletic activities to avoid further reinjuries may do well with an ACL-deficient knee for many years. In addition, patients who led a sedentary lifestyle before the injury may also function adequately without undergoing reconstruction. It appears that some patients with ACL deficiency develop compensatory strategies to deal with problems related to altered neuromuscular control and function, allowing a return to athletic activities in the short-term [28]. However, considering the fact that most patients who sustain ACL ruptures are under the age of 25, athletically active, and are not able to successfully manage deficits in neuromuscular control, it is the authors' experience that the majority are advised to undergo early reconstruction to avoid reinjuries and further joint damage. The well-documented problem of subsequent meniscus tears in ACL-deficient knees leading to premature joint damage lends credence to early joint stabilization.

Many ACL natural history studies have reported that one-third or more of patients required "late" ACL reconstruction after a course of conservative treatment failed due to repeat instability episodes [11, 122, 165]. What is more difficult to ascertain from the literature are the percent of patients who essentially fail conservative management and have symptoms on a frequent basis, but who do not elect reconstruction. There is another group of patients who reduce their activity level and avoid high-risk activities such as cutting and twisting in order to avoid ACL reconstruction, but who may not be entirely satisfied with these self-imposed limits. Thus, the true success rate of conservative treatment of the chronic ACL-deficient knee is not possible to define at present. In the authors' opinion, success constitutes no subsequent giving-way or chronic pain or swelling with the patient's current activities, which are at their desired level.

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Muscle Dysfunction After Anterior Cruciate Ligament Rupture and Reconstruction: Implications for Successful Recovery

3

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Abstract

Lower extremity kinetic chain neuromuscular control and kinematics are of utmost importance of consideration to both prevent anterior cruciate ligament (ACL) injuries and rehabilitate athletes after ACL reconstruction. This chapter investigates the associated muscle dysfunction experienced in the lower limb after ACL injury and reconstruction. In addition, the most recent literature is presented regarding the importance of proper lower limb objective evaluation before return to sports following ACL injury and reconstruction.

3.1 Introduction

Anterior cruciate ligament (ACL) tears remain a common orthopedic injury, with an estimated annual incidence of 69 per 100,000 person-years and a peak incidence in females (228 per 100,000) between 14 and 18 years of age [1]. This injury may not only cause significant pain and potential disability but may lead to altered knee kinematics and recurrent instability events. The pivoting injury that occurs at the time of ACL tear, as well as subsequent recurrent giving-way events, may lead to further meniscal and cartilage damage [2]. Correspondingly, ACL reconstruction remains one of the most commonly performed orthopedic operations today, with approximately 250,000 procedures done annually [3].

Despite the volumes of literature devoted to various surgical reconstructive techniques, there is a relative paucity of data regarding the impact of ACL injury and subsequent ACL reconstruction on the lower limb kinetic chain. The majority of ACL injuries occur via a noncontact pivot mechanism, and a prevailing theory remains that fatigue may induce alteration in the dynamic stabilizers of the knee, resulting in increased strain and failure of the static ACL [4, 5]. Deficits after ACL injury and reconstruction have been observed in various measurements including force output, balance, and neuromuscular control. Proper kinematics, adequate neuromuscular control, and optimum muscle strength are considered critical factors for the return to sports and prevention of reinjury or injury to the contralateral limb [6]. This chapter aims to elucidate the current understanding of hip, knee, and ankle periarticular muscle dysfunction after ACL injury

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and reconstruction and the potential impact of continued muscle disorders to a successful recovery.

3.2 Hip

Muscles about the hip joint are critical for pelvic control, especially during the mid-stance phase of gait. The presence of hip flexion, extension, adduction, and abduction weakness have all been exhibited in various studies following ACL reconstruction [7–9]. In particular, the gluteus medius muscle is the primary abductor of the hip joint and provides eccentric contracture during femoral internal rotation. It has been shown that a high-risk position for noncontact ACL injury is a dynamic valgus load to the knee that is accentuated by femoral internal rotation and adduction [10]. Studies have delineated the importance of hip mechanics and gluteus medius function in maintaining proper lower limb alignment during gait and on landing [11, 12]. Fatigue of the gluteus medius has been theorized to be associated with increased valgus load at the knee because the femur falls into an adducted and internally rotated position, resulting in increased risk of ACL injury [13]. Dalton et al. [14] investigated this hypothesis in 34 knees (17 recreational athletes with unilateral ACL tears 2 years post-ACL reconstruction and matched controls) by recording dynamic single-legged balance electromyographic gluteus muscle activation, single-legged vertical jump height, and maximum isometric strength for hip abduction, extension, and external rotation pre- and post-exercise. Reductions in both the ACL-reconstructed and control group were recorded in hip abduction ($P = 0.04$) and extension ($P = 0.01$) strength after exercise fatigue. However, the ACL-reconstructed group exhibited a greater decrease in hip extensor strength loss compared with the control group ($P = 0.01$). These findings are not entirely surprising, given that more than half of the treatment group underwent ACL reconstruction with a hamstring autograft.

Geoghegan et al. [15] and others have reported a decrease in hip extension strength after hamstring autograft ACL reconstruction 3–12 months postoperatively; however, no significant differences were reported >1 year postoperatively. Contrary to these findings, Thomas et al. [16] compared lower limb strength before and after bone-patellar tendon-bone (B-PT-B) autograft ACL reconstruction (mean, 212 days postoperative) in 30 patients (15 ACL-reconstructed knees and 15 matched controls). No significant difference in hip flexion, extension, abduction, or adduction was found between groups. In the ACL-reconstructed group, increased strength in hip extension was reported in the reconstructed limb compared with the contralateral side, which was most likely a function of successful postoperative rehabilitation or perhaps dominant lower limb sidedness.

Clearly, there is some contradiction of hip muscular dysfunction following ACL injury and reconstruction in the literature, which may be attributed to variance among study designs, but is more likely a function of graft choice and donor-site morbidity than a causative etiology of ACL injury. Rather than strength alone, perhaps hip motion and alignment play a more significant role. VandenBerg et al. [17] investigated an association between hip rotation and risk of ACL injury. These authors measured baseline hip rotation in 25 individuals with an ACL tear and 25 matched controls with no history of an ACL tear. A correlation was found between limited hip internal rotation and risk of ACL tear, because every 10° of increase in hip internal rotation decreased the odds of having an ACL tear by a factor of 0.419. Likewise, Bedi et al. [18] examined 324 football players attending the 2012 National Football League combine and demonstrated a correlation between a reduction in hip internal rotation and increased odds for a history of ACL injury. These investigators determined that a 30° reduction in hip internal rotation was associated with a 4.06 ($P = 0.0001$) and 5.29 ($P < 0.0001$) times greater odds of ACL injury in the ipsilateral and contralateral limbs, respectively. Clearly, it is essential to not only obtain full strength but, perhaps more important, proper hip range of motion and kinetic chain mechanics before return to play in order to decrease the risk for ACL graft rupture or contralateral ACL injury.

The use of a hamstring autograft in ACL reconstruction may have a significant effect on hip muscle function postoperatively. Hiemstra et al. [7] compared hip extension and abduction strength in 15 subjects who were 1 year post semitendinosus-gracilis autograft reconstruction with 15 matched healthy controls. A significant increase in hip extension strength was reported postoperatively ($P < 0.05$); however, isometric hip adduction strength deficits ranging from 36 to 43% compared with controls were also detected (15° flexion dominant limb mean difference 36.8% and nondominant limb mean difference 43.7%; 30° flexion dominant limb mean difference 36.8% and nondominant limb mean difference 43.7%; $P < 0.05$). The investigators hypothesized that the combination of greater hip extension strength and hip adduction weakness may contribute to an increased risk of reinjury, given the aforementioned importance of the hip adductors for proper limb positioning during pivoting and deceleration activities that put increased strain on the ACL graft. Rehabilitation after ACL reconstruction should focus on hip adduction strength because excessive attention to hip extensor strength may contribute to knee-hip strength imbalances, predisposing the patient to reinjury.

Khayambashi et al. [19] performed a prospective case-control study involving 501 competitive athletes in various sports. Baseline hip external rotation and abduction isometric strength was measured before the start of the respective competitive seasons. Fifteen athletes sustained noncontact ACL injuries. This subgroup had significantly lower mean baseline hip strength measures compared with noninjured athletes for external rotation (17.2 ± 2.9% body weight [BW] and 22.1 ± 5.8% BW, respectively, $P = 0.003$) and abduction (30.8 ± 8.4% BW and 37.8 ± 7.6% BW, respectively, $P < 0.001$). Using a logistical regression model, clinical cutoffs believed to define high risk for ACL injury were established for external rotation strength (<20.3% BW) and adduction strength (<35.4% BW). Further research and validation of these measures is required; however, they present a plausible target for ACL injury prevention.

3.3 Knee

The ACL plays an important role in kinematics about the knee, providing static stabilization of the tibia against anterior translation and rotatory forces [20]. The quadriceps and hamstring forces provide dynamic stability to the knee joint. It has long been understood that the hamstring muscles alone provide dynamic stabilization of the ACL-injured knee, whereas the opposing torque of the quadriceps muscle alone exerts a destabilizing force on the anterior tibia. However, together this force-coupling stiffens the knee and attenuates the strain on the ACL; thus, it is essential to maintain proper balance between quadriceps and hamstring force potential [21].

Unfortunately, quadriceps and hamstring strength deficits in the injured lower extremity are commonly reported following ACL injury and reconstruction. These can often persist beyond the postoperative rehabilitation phase and may compromise graft integrity with premature return to play. Compared with the contralateral leg, quadriceps strength deficits in the injured leg after ACL injury and reconstruction have been reported to range from 5 to 30% and hamstring strength deficits from 9 to 13% [22–25]. de Jong et al. [23] performed a retrospective review of 191 patients who underwent ACL reconstruction with either B-PT-B or hamstring autografts and evaluated their pre- and postoperative quadriceps and hamstring strength (Table 3.1). A persistent quadriceps strength deficit of nearly 20% ($P = 0.01$) was found at 1 year postoperative; however, hamstring strength returned to normal levels within 6–12 months. These investigators also identified an intuitive relationship between increased quadriceps strength deficits and B-PT-B autograft, as well as between flexion strength deficits and hamstring autograft (Table 3.2). Their data suggest that perhaps the flexion strength deficit is better tolerated and responsive to postsurgical rehabilitation than quadriceps strength deficit. Similarly, Xergia et al. [26] performed a meta-analysis and found that patients with autologous B-PT-B ACL reconstruction had greater quadriceps weakness relative to hamstring weakness compared with

Table 3.1 Mean isokinetic quadriceps and hamstring strength deficits before and after ACL reconstruction[a]

Muscle	Test speed	Time period	No. of patients	Strength deficit (%) Involved-noninvolved	
				Mean ± SD	Range
Quadriceps	60°/s	Preoperative	137	17 ± 16	−13 to 77
		6 mos p.o.	114	36 ± 15	−11 to 74
		9 mos p.o.	102	25 ± 15	−15 to 61
		12 mos p.o.	53	19 ± 13	−11 to 42
	180°/s	Preoperative	136	12 ± 14	−26 to 72
		6 mos p.o.	114	25 ± 12	−5 to 58
		9 mos p.o.	102	18 ± 13	−16 to 55
		12 mos p.o.	52	16 ± 11	−14 to 54
Hamstrings	60°/s	Preoperative	135	5 ± 15	−51 to 46
		6 mos p.o.	114	6 ± 14	−25 to 38
		9 mos p.o.	102	4 ± 14	−34 to 33
		12 mos p.o.	53	−1 ± 14	−52 to 33
	180°/s	Preoperative	134	4 ± 21	−157 to 66
		6 mos p.o.	112	5 ± 14	−49 to 42
		9 mos p.o.	102	5 ± 13	−25 to 41
		12 mos p.o.	52	1 ± 11	−33 to 25

[a]Adapted from de Jong et al. [23]

Table 3.2 Mean isokinetic quadriceps and hamstring strength deficits influenced by graft choice[a]

Time period	Quadriceps deficit 60°/s			Hamstring deficit 60°/s		
	B-PT-B (%)	STG (%)	*P* value	B-PT-B (%)	STG (%)	*P* value
Preoperative	17	18	NS	4	11	NS
6 mos p.o.	37	26	0.007	5	17	0.003
9 mos p.o.	27	17	0.03	2	15	<0.001
12 mos p.o.	21	7	0.01	−2	4	NS

[a]Adapted from de Jong et al. [23]

B-PT-B bone-patellar tendon-bone, *NS* not significant, *STG* semitendinosus-gracilis tendon

patients with autologous hamstring ACL reconstruction at the 2-year postoperative time point.

Thomas et al. [16] investigated quadriceps and hamstring strength in ACL-injured knees pre- and postoperatively in 15 individuals who underwent B-PT-B autograft reconstruction and compared the data with 15 matched controls. Decreased knee extensor strength was detected preoperatively (35% less than the uninjured side, $P = 0.001$) and postoperatively (33% less than the uninjured side, $P < 0.001$). In addition, decreased knee flexor strength was found preoperatively (31% less than the uninjured side, $P < 0.001$) and postoperatively (11% less than the uninjured side, $P = 0.006$). This continued knee extensor and flexor muscle weakness is concerning given the important role of dynamic stabilization of the knee, and perhaps improving rehabilitation strategies to better target and measure this weakness may decrease reinjury rates.

Wright et al. [27] performed a systematic review investigating the rate of ipsilateral graft and contralateral ACL injury following ACL reconstruction at 5 years postoperatively. These investigators determined a pooled percentage of tears to the contralateral ACL to be twice (11.8%) that of ACL graft rupture (5.8%). Concerned that inadequate neuromuscular rehabilitation of the contralateral limb may be contributory, Chung et al. [28] tested knee flexor and extensor strength postoperatively in 75 patients who underwent ACL hamstring autograft reconstruction in both the reconstructed and contralateral limbs and in a group of matched controls. Reductions in isokinetic extensor strength, single-leg hop performance, and functional status of both limbs were found at 2 years postoperatively. However, knee flexor strength returned to normal levels in both limbs. This study highlights the importance of directing postoperative rehabilitation toward both knee flexors and extensors regardless of graft choice and on both limbs to prevent reinjury to either the healing graft or contralateral ACL.

3.4 Ankle

Although most research on lower extremity muscles surrounding ACL injury and reconstruction has focused on the hamstrings and quadriceps, the muscles that cross the ankle joint are also impacted by the injury and/or surgery. Prior studies have demonstrated that calf and ankle muscles are negatively affected by an ACL injury and their reeducation should be included in a rehabilitation program.

Dingenen et al. [29] examined the muscle activation onset times (MAOT) for multiple lower extremity muscles including the tibialis anterior, peroneus longus, and gastrocnemius. When compared with uninjured controls, the ACL-injured cohort showed delayed MAOT of the tibialis anterior with the patients' eyes open ($P < 0.001$) and delayed MAOT of the gastrocnemius with eyes closed ($P < 0.05$) and concluded that central nervous system reeducation training is an important aspect of recovery. A separate study by the same authors demonstrated that even after completing an ACL-specific rehabilitation program and returning to sport, the gastrocnemius continued to show a significantly delayed MOAT ($P = 0.05$) [30].

In a study examining muscle size using magnetic resonance imaging, Norte et al. [31] showed that patients undergoing ACL reconstruction have decreased tibialis anterior muscle volume compared with healthy individuals preoperatively (0.8 ± 0.1 cm^3/kg*m and 1.0 ± 0.1 cm^3/kg*m, respectively) and postoperatively (0.8 ± 0.1 cm^3/kg*m and 0.9 ± 0.0 cm^3/kg*m, respectively). In an attempt to minimize the impact of muscle atrophy due to the relative immobilization and weight-bearing restriction after ACL reconstruction, Hasegawa et al. [32] randomized 20 patients to either electrical muscle stimulation (EMS) in addition to standard rehabilitation or to standard rehabilitation alone. The EMS cohort demonstrated a significant increase in calf size at 4 weeks after surgery ($P = 0.016$), whereas there was a significant decrease in the standard rehabilitation alone cohort ($P = 0.0002$).

Despite the seemingly consistently reported calf muscle size reduction surrounding ACL reconstruction, ankle strength has been examined with conflicting results. Using an isokinetic testing protocol, Karanikas et al. [9] demonstrated no significant difference in ankle dorsiflexion or plantarflexion strength between injured and uninjured extremities following ACL reconstruction at various postoperative periods (3–6 months, 6–12 months, and 12–24 months). For example, at 3–6 months, the maximum dorsiflexion moment was 27 ± 6.3 Nm in the injured leg and 27 ± 5.6 Nm in the uninjured extremity. In addition, no difference in kinematic parameters around the ankle was noted between limbs while walking and running. However, Thomas et al. [16] found that during isokinetic dynamometer testing, ankle plantarflexion was significantly weaker preoperatively than at 6 months following ACL reconstruction (mean difference, 31.9%; $P = 0.006$).

3.5 Summary

The aim of ACL reconstruction in athletes is to allow for safe and expeditious return to desired activities at the preinjury level. Despite advancements in surgical instrumentation, operative techniques, and graft choice stratification, there has been a relative paucity of information or consensus on appropriate postoperative rehabilitation protocols and return-to-play criteria that objectively assesses muscle recovery and functional response to confer sufficient dynamic stability to the injured knee. Time after surgery has been an important criterion for graft incorporation; however, ACL graft reinjury rates vary from 0 to 19%

across the literature, and tear rates of the contralateral ACL range from 7 to 24% [33–35]. There are many factors that may contribute to these problems, but lower limb neuromuscular control, kinematics, and muscle strength clearly play in integral role in ACL injury prevention. Lower limb alignment, mobility, strength, and kinetic chain mechanics also play important roles in maximizing the static and dynamic stability of the knee. Isokinetic examination of the hip, knee, and ankle should be performed postoperatively because weakness may directly impact not only return to play but graft retear or contralateral ACL injury rates. These findings have implications for design of neuromuscular training, rehabilitation protocols, and objective testing to prevent dynamic valgus loading at the knee prior to return to play after ACL reconstruction.

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4

Risks of Future Joint Arthritis and Reinjury After ACL Reconstruction

Frank R. Noyes and Sue Barber-Westin

Abstract

This chapter discusses long-term data from ACL reconstruction studies, the factors that are most likely related to increased risk of developing arthritis, and causes of failure of surgery. While data from most ACL reconstruction studies show favorable results in terms of improved knee stability and function, the outcome in terms of prevalence of osteoarthritis in long-term studies is highly variable. Factors that may cause eventual knee arthritis include meniscectomy, abnormal knee kinematics, severe bone bruising, damage to other knee ligament structures, alteration in the biochemical environment, chondral fractures or lesions, excessive uncorrected varus or valgus lower limb malalignment, obesity, genetics, and long-term participation in high-impact sports activities. The problem exists that ACL reconstruction does not fully restore normal knee kinematics, despite advanced surgical procedures and rehabilitation. The published rates of either reinjuring an ACL-reconstructed knee or sustaining an ACL rupture on the contralateral knee upon return to activities after surgery vary widely from 2 to 30%.

4.1 Introduction

The goals of anterior cruciate ligament (ACL) reconstruction are to restore stability to the knee joint, prevent future injuries, return patients to desired activity levels, and prevent or delay the onset of knee joint osteoarthritis (OA). While data from most studies show favorable results in terms of improved knee stability and function, the outcome in terms of prevalence of OA in long-term studies is highly variable. Many investigators have stated that the ACL injury itself may lead of OA regardless of the treatment selected and subsequent joint loading over ensuing years [1–6]. Factors that may cause eventual OA include meniscectomy (either with the ACL reconstruction or subsequently from a reinjury), severe bone bruising, damage to other knee ligament structures, excessive uncorrected varus or valgus lower limb malalignment, biochemical factors, and chondral fractures or lesions [5, 7–9]. Other factors that may play a role include obesity, genetics, abnormal knee kinematics after ACL reconstruction, and long-term participation in high-impact sports activities [3–6].

ACL reconstruction does not fully restore normal knee kinematics, despite advanced surgical

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procedures and rehabilitation. The native ACL is a complex structure composed of individual fibers and fiber regions that are loaded throughout knee motion to resist anterior tibial translation and rotational instability, as with the combined motions of anterior tibial translation and internal tibial rotation in the pivot-shift test [10–12]. Studies have documented the problem of vertical ACL graft orientation that results from improper tunnel placement (Fig. 4.1) [13–15]. In some patients, this graft orientation results in a return of a positive pivot shift, knee instability, subsequent revision ACL reconstruction [14], and eventual OA.

Fig. 4.1 Anteroposterior and lateral radiographs and MRI images of patients who presented to our center for anterior cruciate ligament (ACL) revision with a vertical ACL graft. The femoral graft location is primarily on the notch roof. In our experience, this vertical graft orientation is the primary cause for ACL failure. (Reprinted from Noyes FR, Barber-Westin SD (2017) Anterior cruciate ligament revision reconstruction: graft options and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 221–257)

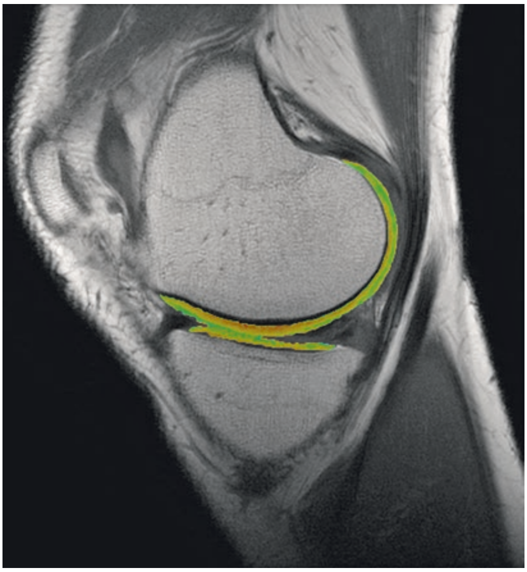

Fig. 4.2 T2 mapping from a 3-Tesla MRI shows intact articular cartilage with no focal prolongation of relaxation times. (Reprinted from Noyes FR, Barber-Westin SD (2017) Meniscus tears: diagnosis, surgical techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 677–718)

One problem in the understanding of the ability of ACL reconstruction to prevent or delay the onset of OA is the lack of prospective, randomized Level 1 studies that compare operative with conservative management of this injury using modern operative procedures and rehabilitation programs [16]. Secondly, while studies historically have used plain radiographs to rate OA, more advanced technology is now available such as magnetic resonance imaging (MRI) with T2 mapping [9, 17, 18] which determines with higher accuracy the status of the articular cartilage (Fig. 4.2). To date, few investigations have used this technology to document OA changes longitudinally after ACL injury and reconstruction.

Critical Points

- Outcome ACL reconstruction regarding prevalence of osteoarthritis in long-term studies highly variable.
- Factors that may cause osteoarthritis: meniscectomy, severe bone bruising, damage to other knee ligaments, alteration in biochemical environment, chondral fractures, uncorrected varus or valgus malalignment, obesity, genetics, and long-term participation in high-impact sports activities.
- ACL reconstruction does not fully restore normal knee kinematics.
- Few prospective, randomized Level 1 studies available that compare operative and conservative management of ACL injuries.

4.2 Risk Factors for Osteoarthritis After ACL Reconstruction

Published rates of radiographic OA after ACL reconstruction vary tremendously (Table 4.1) [2, 5, 19–36]. Studies typically use weight-bearing anteroposterior (AP) and posteroanterior radiographs, as well as lateral and Merchant, to determine the presence and severity of OA, although a few have used MRI [21, 22, 36–38] or computed tomography [39]. The two most commonly used radiographic rating systems to classify OA are the Kellgren-Lawrence (K-L) [40] and the International Knee Documentation Committee (IKDC) system [41].

Studies have shown that, regardless of the outcome of ACL reconstruction in terms of restoration of knee stability, meniscectomy accelerates degenerative joint changes (Fig. 4.3) [2, 5, 19, 20, 26, 32, 42, 43]. 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. We conducted a systematic review of the treatment of meniscus tears during ACL reconstruction of studies published from 2001 to 2011 [44]. 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

Table 4.1 Prevalence of radiographic osteoarthritis in long-term ACL reconstruction studies

Study	No. of patients Mean follow-up year (y)	ACL graft (failure rate[a])	OA KL grade 0–1 IKDC normal, nearly normal	OA KL grade 2–3 IKDC abnormal, severely abnormal	Statistically significant risk factors for OA
Thompson et al. [35]	90 20 y	BPTB autograft (9%)	80%	20%	NA
Gerhard et al. [20]	63 16 y	BPTB autograft (3%)	77%	23%	Meniscectomy
Oiestad et al. [29]	181 12.3 y	BPTB autograft (8%)	74%	26%	Increased age, poor quadriceps strength
Holm et al. [23]	53 11.8 y	BPTB autograft (21%)	20%	80%	Meniscectomy, chronicity of injury
Ahn et al. [19]	117 10.3 y	BPTB autograft (9%)	69%	31%	Partial meniscectomy and sagittal tibial tunnel position in medial compartment, BMI in lateral compartment
Murray et al. [28]	83 13 y	BPTB autograft (17%)	60%	40%	Meniscectomy, preexisting chondral damage
Shelbourne and Gray [32]	502 14.1 y	BPTB autograft (1%)	77% (pts with bilateral meniscectomies) 95% (pts with intact menisci)	23% (pts with bilateral meniscectomies) 4% (pts with intact menisci)	Meniscectomy, preexisting chondral damage
Pernin et al. [48]	100 24.5 y	BPTB autograft + iliotibial band extra-articular procedure (20%)	46%	54%	Meniscectomy, preexisting chondral damage, time to surgery, higher age at injury and surgery
Inderhaug et al. [24]	83 10.2 y	STG autograft (20%)	92%	8%	Meniscectomy
Struewer et al. [34]	52 10.2 y	STG autograft (3%)	75%	25%	Increased anterior tibial displacement
Streich et al. [33]	40 10 y	STG autograft (8%)	93%	7%	Positive pivot shift, high BMI
Janssen et al. [25]	88 10 y	STG autograft (NA)	46%	54%	Medial meniscectomy, age ≥ 30 year, preexisting chondral damage
Barenius et al. [2]	134 14 y	BPTB autograft (4%) ST autograft (5%)	BPTB 45% ST 30%	BPTB 55% ST 70%	Meniscectomy, age at follow-up, BMI ≥ 25 kg/m^2, manual labor, positive pivot shift

Hoffelner et al. [22]	28 10 y	BPTB autograft STG autograft Overall failure rate 3%	Overall 80%	Overall 20%	NA
Wipfler et al. [36]	54 8.8 y	BPTB autograft (10%) STG autograft (12%)	BPTB 70% STG 65%	BPTB 30% STG 35%	NA
Keays et al. [26]	56 6 y	BPTB autograft (0%) STG autograft (7%)	BPTB 76% STG 100%	BPTB 24% STG 0%	Meniscectomy, preexisting chondral damage, BPTB graft, weak quadriceps, low quadriceps/hamstrings ratio
Hanypsiak et al. [21]	44 12.7 y	BPTB or STG autograft Overall failure rate 23%	68%	32%	Meniscectomy
Pinczewski et al. [30]	128 10 y	BPTB autograft (8%) STG autograft (13%)	BPTB 97% STG 99%	BPTB 3% STG 1%	Poor performance single-leg hop test, use of BPTB graft
Kessler et al. [27]	60 11.1 y	BPTB allograft (NA)	55%	45%	Higher age at surgery, higher BMI
Sanders et al. [31]	600 13.7 y	BPTB or STG autograft or allograft (NA)	NA	8.5%	Age > 21 at injury, meniscectomy, preexisting chondral damage, use of allograft
Li et al. [5]	249 7.8 y	BPTB or STG autograft or allograft Overall failure rate 13%	74%	26%	BMI > 25 kg/m^2, medial meniscectomy, preexisting chondral damage, length of follow-up

AP anteroposterior, *BMI* body mass index, *BPTB* bone-patellar tendon-bone, *IKDC* Internal Knee Documentation Committee, *NA* not available, *OA* osteoarthritis, *STG* semitendinosus-gracilis

OA grade = KL (Kellgren-Lawrence), IKDC (International Knee Documentation Committee) rating systems

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

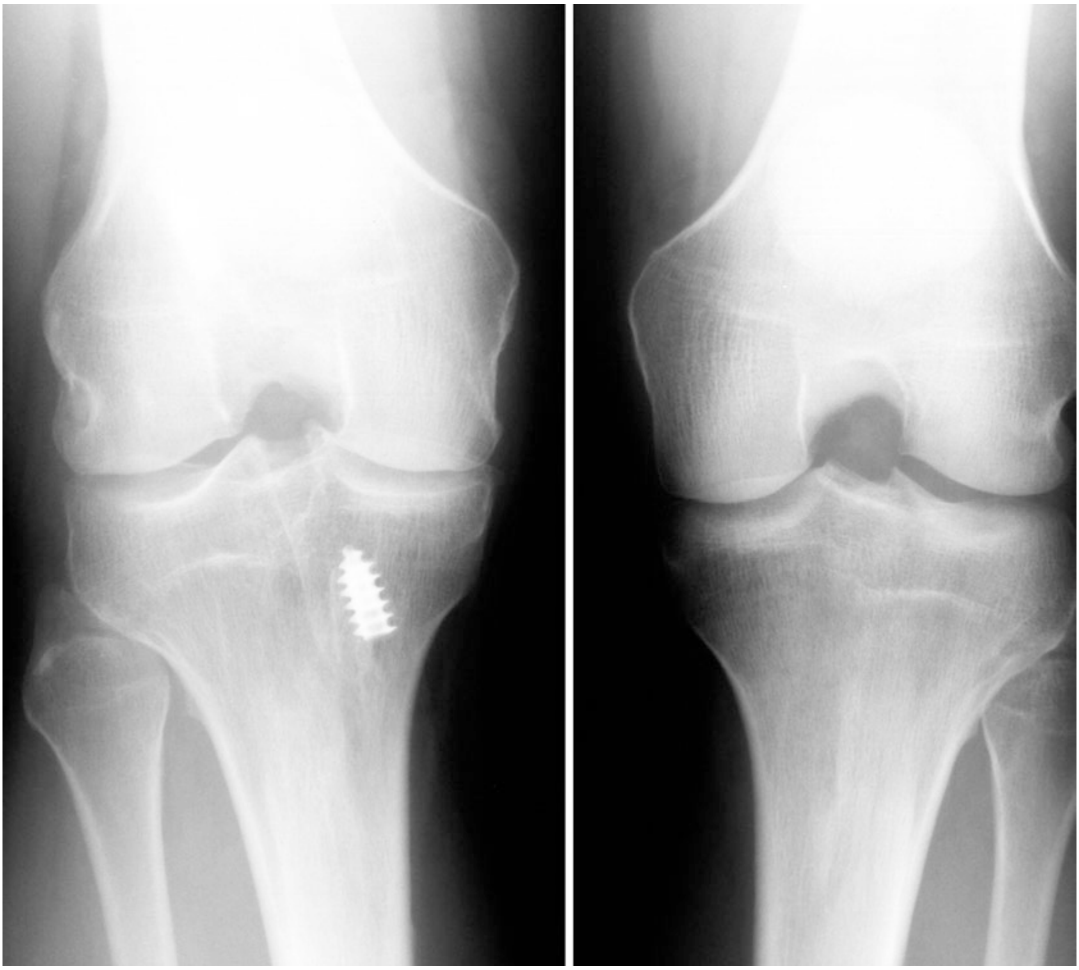

Fig. 4.3 Standing radiographs of a patient 14 years after a right ACL reconstruction and subsequent medial meniscectomy. The pivot-shift test was negative, indicating a stable reconstruction. However, narrowing to the medial tibiofemoral compartment is evident and the patient demonstrated 2° of varus alignment. (Reprinted from Noyes FR, Barber-Westin SD (2017) Meniscus tears: diagnosis, surgical techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 677–718)

structure. This topic is discussed in further detail in Sect. 4.7.

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, older patient age, elevated body mass index (BMI), failure of the reconstruction to restore normal AP displacement, complications (such as infection, arthrofibrosis), and poor quadriceps strength. In many studies, these variables are not controlled for, making reaching conclusions on these factors difficult.

It is also important to note that the majority of OA findings reported in the literature are mild or moderate (IKDC ratings of B or C) and 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 after ACL reconstruction [45–48]. As investigations obtain longer follow-up periods, one may speculate that the OA findings will become more severe and correlate with clinical symptoms such as loss of extension and swelling with daily activities.

Claes et al. [16] systematically reviewed 16 long-term ACL reconstruction studies (follow-up range, 10–24.5 years) involving 1554 subjects. The investigators converted all radiographic data into IKDC ratings and reported that the combined estimate for the prevalence of 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 (odds ratio [OR] 3.54).

Barenius et al. [2] followed 164 patients a mean of 14 years after ACL reconstruction (randomized using bone-patellar tendon-bone [BPTB] or semitendinosus autografts). Radiographic, symptomatic OA (K-L grade ≥ 2) was detected 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 BPTB 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.

Salmon et al. [43] conducted a longitudinal analysis of 49 patients followed for 13 years after ACL BPTB autograft reconstruction. At the final follow-up, 96% had no giving-way with moderate or strenuous activities and 92% had no pain with these activities. The prevalence of radiographic OA (IKDC ratings of C or D) increased from 5 years postoperative (2%) to 13 years postoperative (21%, $P = 0.01$). Poor radiographic grades were significantly associated with medial meniscectomy done at the time of ACL reconstruction ($P = 0.006$).

Pinczewski et al. [30] compared the results of 74 patients who underwent ACL reconstruction with a semitendinosus-gracilis (STG) autograft with 75 patients who underwent BPTB autograft reconstruction. The menisci were intact in all subjects. At 10 years postoperative, IKDC grade C OA changes were noted in just 3% of the BPTB group and in 1% of the STG group.

Critical Points

- 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.
- Majority OA mild or moderate; presence of associated symptoms not reported in most studies.
- Other risk factors associated with OA after ACL reconstruction include preexisting chondral damage, patient age, body mass index, failure of the reconstruction to restore normal anteroposterior displacement, complications, and poor quadriceps strength.

4.3 Osteochondral Lesions (Bone Bruises) with ACL Injury

Occult injuries to the bone, commonly referred to as bone bruises, occur with ACL ruptures in 80–100% of knees (Fig. 4.4) [18, 49–54]. The injury causes an anterior subluxation of the tibia relative to the femur that results in the lateral femoral condyle impacting against the lateral

Fig. 4.4 Bone bruise on MRI following rupture of the ACL

tibial plateau. Therefore, the majority of bone bruises that occur during ACL injuries are located on the lateral femoral condyle and the posterolateral tibial plateau [18, 49, 55, 56], although medial-sided bone contusions have been reported [49, 54]. Bone bruises are believed to be the result of microfracture of the medullary trabeculae and hemorrhage that occurs at the time of the injury [57] and vary in severity. In many knees, plain radiographs and arthroscopy show no abnormalities, and the bone bruise is only evident on MRI. Other osseous injuries may occur during ACL ruptures, including subchondral fractures, osteochondral fractures, and stress fractures [54, 58, 59].

In a study of 171 acute ACL injuries, Bisson et al. examined predictors of the presence and severity of bone bruising [49]. More severe bone bruising on the lateral femoral condyle was associated with age at injury of ≤17 years (compared with ages ≥18) and male gender. More severe bone bruising on the lateral tibial plateau was associated with male gender and contact injuries. The presence of a lateral femoral condyle bone bruise was associated with increased odds (OR 2.57) of a concomitant lateral meniscus tear.

The natural history of bone bruises associated with ACL injuries remains unclear. However, studies that longitudinally followed patients with acute ACL ruptures for several years have demonstrated a strong potential for joint deterioration. Potter et al. prospectively followed 40 patients who underwent baseline MRI within 8 weeks of the injury and again 7–11 years later [18]. 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 nonsurgical group had a significantly higher OR effect of cartilage loss over the medial tibial plateau compared with the surgical group.

Frobell [60] 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. Potter et al. [61] remarked that the chondral injury sustained at the time of ACL injury affects not only cartilage morphology but may deplete the extracellular matrix over the area of the bone bruise that could deleteriously affect other cartilage surfaces of the knee joint.

Theologis et al. [9] conducted a longitudinal analysis of nine patients with acute ACL injuries with $T_{1\rho}$ MRI techniques to quantify the volume and signal intensity of bone marrow edema-like lesions. This advanced imaging technique determines interactions between water molecules and the cartilage extracellular matrix; an increase in the $T_{1\rho}$ value represents damage to the matrix. Images were obtained within 8 weeks of the injury and then 2 weeks, 6 months, and 12 months after ACL reconstruction. The authors reported that the cartilage overlying the lesions on the lateral tibia showed significantly increased $T_{1\rho}$ values compared with surrounding cartilage at all follow-up time periods. Elevated $T_{1\rho}$ values also persisted in the medial tibia and condyle. The superficial layers of the overlying cartilage showed greater matrix damage than the deep layers. The results suggested that the volume of lesions on the lateral tibia may be used to predict the degree of damage to the overlying cartilage in that compartment.

A high association between bone bruises and articular cartilage damage observed at arthroscopy was reported by Nishimori et al. [51]. In a study of 39 patients who underwent ACL STG reconstruction, 90% had bone bruises in the lateral compartment. Of these, 94% had articular cartilage lesions on the lateral femoral condyle and 80% on the posterolateral tibial plateau. Although the lesions were rated as either grade 1 (softening) or grade 2 (fibrillation), the authors noted that they could act as a catalyst to cause future OA, even after a successful ACL reconstruction.

Other studies have reported that bone bruises resolve with time [21, 53, 60]. Yoon et al. [53], in a study involving 145 ACL-injured knees, reported prevalence rates of >80% in acute and subacute time periods (<3 months of the injury), 57% in the intermediate time period (3 months to 1 year), and 11% in the chronic time period (>1 year). The investigators compared the signal intensity values of the bone bruises with those of adjacent normal bone marrow. Hanypsiak et al. [21] followed 44 patients who received ACL reconstruction for an acute injury for 12 years postoperative. Although 36 had a bone bruise on their preoperative MRI, none were evident on follow-up MRI.

Occult osteochondral lesions vary, and therefore, the relationship between the presence of these injuries with ACL ruptures and subsequent OA remains unclear. However, evidence does exist that the most severe injuries are associated with future cartilage degeneration and they therefore should be considered part of the sequela of posttraumatic OA.

Critical Points

- 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 posttraumatic OA.

4.4 Biochemical Alterations Following ACL Injury

ACL ruptures create biochemical alterations in the knee joint which many authors believe play a major role in the development of OA [62–76]. The cascade of events, summarized in Table 4.2, begins immediately after the injury and continues for years thereafter [62, 75]. The injury itself 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.

Cuellar et al. [63] reported significantly higher concentrations of four proinflammatory cytokines in synovial fluid in 12 patients who had an

Table 4.2 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 (intra-articular joint bleeding)
• Elevated levels of GAG
• Cell necrosis
Subacute (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 remodeling
• Articular cartilage deterioration, loss

GAG glycosaminoglycan, *MMP* metalloproteinase, *TNFα* tumor necrosis factor α acute ACL injury (≤6 weeks) compared with controls. For instance, IL-6 was elevated (105 ± 72 pg/mL versus 0; $P < 0.001$), which was in agreement with findings of several other studies [64, 66, 75, 77]. Higuchi et al. [66] investigated concentrations of cytokines, MMPs, and tissue inhibitors of metalloproteinases (TIMP) in synovial fluid in 32 knees 2–134 weeks after ACL injury. Higher levels of IL-6, MMP-3, and TIMP-1 were found compared with normal knees. The concentration of MMP-3 remained elevated regardless of the amount of time that had elapsed after injury.

Papathanasiou et al. [74] found significant associations between time from ACL rupture and levels of MMP-13, the major catabolic enzyme of articular cartilage destruction, and levels of IL-1β and IL-6. A significant upregulation of MMP-13 was observed in patients with chronic ACL ruptures (>18 months) compared with those with ACL ruptures that occurred ≤18 months previously. Increased levels of IL-1β and IL-6 were found in patients with ACL ruptures that occurred >10 months compared with those with ACL ruptures that occurred ≤10 months previously.

Struglics et al. [75] longitudinally followed 121 patients for 5 years after acute ACL injury. Within 6 weeks of the injury, significantly higher levels of IL-6, IL-8, IL-10, and TNF were found compared with a control group; the differences ranged from 1050-fold (IL-6) to 6-fold (TNF). TNF was the only cytokine to remain elevated for the entire study period. Similar findings regarding elevated levels of TNF in chronic ACL-deficient knees were also reported by Bigoni et al. [62].

Lohmander et al. [78] reported that the level of cartilage proteoglycan fragments in synovial fluid following acute ACL rupture in 270 patients was greatly increased compared with normal knees. In many patients, this elevation was observed several years after the injury. In another investigation, Lohmander et al. [70] reported the release of soluble molecular fragments specific for the degradation of mature articular cartilage (type II) into synovial fluid after ACL injury. The concentrations of crosslinked C-telopeptide fragments of type II collagen were significantly higher ($P < 0.001$) compared with a control group at all time intervals studied (1–1000 weeks after injury). The authors concluded that the data provided strong evidence that the integrity of type II collagen network was compromised soon after injury.

Critical Points

- ACL injury causes collagen rupture, joint hemarthrosis, subchondral bone edema, elevated glycosaminoglycan levels, and cell necrosis.
- In the ensuing months, the inflammatory process (elevated levels of several cytokine mediators), decrease in lubricin concentrations, release of enzymes, production of metalloproteinase, release of cartilage proteoglycan fragments and type II collagen, degradation of the extracellular matrix and proteoglycans, chondrocyte apoptosis, and cell death all contribute to articular cartilage deterioration.

4.5 Reinjury and Failure Rates Following ACL Reconstruction

The published rates of either reinjuring an ACL-reconstructed knee or sustaining an ACL rupture on the contralateral knee vary widely (Table 4.3) [4, 30, 35, 43, 79–94]. Some of the most frequently cited factors statistically associated with reinjuries to either knee are younger patient age, return to high-impact sports (cutting, pivoting), and use of an allograft or STG autograft. Unfortunately, the data from studies do not always agree, the postoperative rehabilitation programs are not provided or detailed, patients are lost to follow-up, the mechanisms of the reinjuries are not always given, and reinjury rates are sometimes calculated within short-term time periods. Importantly, the determination of failure rates also varies between studies, because while some use only ACL revision as an indicator of failure, others also incorporate pivot-shift and Lachman (grade 2 or 3) clinical examination results.

Table 4.3 Rates of reinjury in ACL-reconstructed and contralateral knees

Study	Mean follow-up, years	ACL graft, no.	Failed ACL reconstruction[a]	Injured ACL contralateral knee	Factors associated with reinjuries, ACL graft failures
Wiggins et al. [94]	4.2	NA, 72,054 all knees 70,733 < 25 years age 18,468 < 25 years age, returned high-risk sports	7% 21% 10%	8% 11% 12%	Age < 25 year, return to high-risk cutting, pivoting sports
Thompson et al. [35]	20.4	BPTB autograft, 90	9%	30%	Coronal graft angle <17° for ACL-reconstructed knee Age < 18 year for contralateral knee
Shelbourne et al. [92]	5	BPTB autograft, 1415	4%	5%	Age < 18 year, participation in basketball or soccer for either knee Female gender for contralateral knee
Salmon et al. [43]	5–13	BPTB autograft, 67	13%	22%	Age < 21 year, meniscectomy for ACL-reconstructed knee
Webster and Feller [93]	5	STG autograft, 316	18%	18%	Male gender, male age < 18 year for ACL-reconstructed knee
Schlumberger et al. [91]	5	STG autograft, 2467	3%	3%	Male gender, age < 25 year for ACL-reconstructed knee
Faltstrom et al. [80]	5	STG autograft, 20,824	4.3%	3.8%	Age < 16 year, time from injury to surgery (within 90 days), injured playing soccer
Park et al. [87]	4.5	STG autograft, 296	4%	NA	Grafts <8 mm in diameter
Kamien et al. [83]	> 2	STG autograft, 98	15%	NA	Age ≤ 25 year
Magnussen et al. [84]	1.2	STG autograft, 256	7%	NA	Age < 20 year, grafts <8 mm in diameter
Morgan et al. [86]	15	STG autograft, 194 BPTB autograft, 48 Total, 242	19.5% 8% 17%	17.5% 29% 20%	Family history ACL injury for ACL-reconstructed knee Male gender, return to cutting, pivoting sports contralateral knee
Persson et al. [89]	4	BPTB autograft, 3428 STG autograft, 9215 Total, 12,643	2% 5.1% 4.2%	NA NA NA	STG autograft, younger age
Dekker et al. [79]	4	BPTB autograft, 13 STG autograft, 62 STG autograft + allograft, 10	NA NA NA	NA NA NA	Overall, 32% sustained subsequent ACL injury, 19% ipsilateral ACL, 13% contralateral ACL, 1% both knees Time to return to sport
Kaeding et al. [82]	2	BPTB autograft, 1131 STG autograft, 891 Allograft, 466 Total, 2488	3.2% 4.6% 6.9% 4.4%	NA NA NA 3.5%	Allograft, younger age, higher activity levels for ACL-reconstructed knee Younger age, higher activity levels for contralateral knee

(continued)

Table 4.3 (continued)

Study	Mean follow-up, years	ACL graft, no.	Failed ACL reconstruction[a]	Injured ACL contralateral knee	Factors associated with reinjuries, ACL graft failures
Maletis et al. [85]	2.4	BPTB autograft, 4231 STG autograft, 5338 Allograft, 7116 Total, 16,685	1.9% 2.4% 2.8% 2.5%	1.9% 1.8% 1.5% 1.9%	Allograft or STG autograft, male gender, younger age, BMI ≥ 25 for ACL-reconstructed knee Female gender, younger age, BPTB autograft for contralateral knee
Paterno et al. [88]	2	BPTB autograft, 39 STG autograft, 33 Allograft, 6 Total, 78	NA NA NA 9%	NA NA NA 20.5%	Not analyzed
Hettrich et al. [81]	6	BPTB autograft, 469 STG autograft, 343 Allograft, 168 Total, 980	4.1% 6.1% 21.2% 7.7%	NA NA NA 6.4%	Allografts, younger age
Pinczewski et al. [30]	10	BPTB autograft, 90 STG autograft, 90 Total, 180	8% 13% 11%	22% 10% 16%	Increased laxity for ACL-reconstructed knees Age < 21 year for contralateral knee
Ponce et al. [90]	NA	All graft types combined, 2898	2.2% autograft 3.1% allograft	NA	Age, type of sport, surgeon

ACL anterior cruciate ligament, *BPTB* bone-patellar tendon-bone, *NA* not available, *STG* semitendinosus-gracilis

[a] 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

In a meta-analysis of data from 19 studies involving 72,054 patients, Wiggins et al. [94] reported pooled reinjury rates of 7% for the ACL-reconstructed knee and 8% for the contralateral knee. In patients less than 25 years old, the pooled reinjury rates were 21% for the ACL-reconstructed knee and 11% for the contralateral knee. In athletes less than 25 years of age who returned to high-risk sports involving pivoting and cutting after surgery, the pooled secondary ACL injury rate (to either knee) was 23%.

Thompson et al. [35] longitudinally followed 90 patients for 20 years after isolated ACL BPTB autograft reconstruction. This series excluded patients with concomitant ligament ruptures, associated articular cartilage damage, prior meniscectomy, concurrent meniscectomy of more than 30%, abnormal radiographs, or problems with the contralateral knee. At final follow-up, 32 patients had sustained either a rupture to the ACL graft (9%) or to the contralateral ACL (30%). ACL graft ruptures were associated with vertical graft angle, because patients with a coronal graft inclination angle $<17°$ had 8.5 times greater odds of ACL graft failure ($P = 0.01$). Contralateral ACL ruptures were associated with age of <18 years, because these patients had a 3.2 times greater odds of injury compared to those >18 years old ($P = 0.001$).

Shelbourne et al. [92] reported a 9.6% overall reinjury rate 5 years postoperatively in a group of 1415 patients who underwent ACL BPTB autograft reconstruction. The risk of subsequent injury to either knee was 17% for patients <18 years of age compared with 7% for patients 18–25 years and 4% for patients >25 years. Women had a 7.8% incidence of ACL injury in the contralateral knee and a 4.3% incidence in the ACL-reconstructed knee. Men had a similar incidence of injury in both knees (3.7% contralateral knee and 4.1% reconstructed knee). The authors attributed the reinjuries to the high-risk sports patients had returned to, with basketball and soccer accounting for 67% of the reinjuries.

Two studies [84, 87] involving over 550 knees found a significant association between the size of ACL STG autografts and increased risk of failure; grafts <8.0 mm in diameter were more likely to fail than those 8.0 mm or larger. Persson et al. [89] analyzed data on 12,643 patients from the Norwegian Cruciate Ligament Registry who underwent either BPTB or STG autograft reconstruction. Within 5 years postoperatively, patients who were 15–19 years of age with STG grafts had nearly three times the risk of revision as those with BPTB grafts (9.5% and 3.5%, respectively). The use of an allograft was found to be associated with a higher failure rate compared with autografts in several studies with large cohorts [81, 82, 85].

Dekker et al. [79] followed 85 patients who were <18 years of age at the time of ACL autograft reconstruction a mean of 4 years postoperatively. Although 91% returned to sports activities, 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).

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.

4.6 Other Causes of Failure of ACL Reconstructions

Other than a reinjury, ACL reconstructions may fail for a variety of reasons. These include:

1. Errors in surgical technique: improper placement of the ACL graft, use of low-strength grafts, inadequate fixation, graft impingement in the notch, or excessive or insufficient graft tensioning at surgery
2. Biological failure of graft integration, tendon-to-bone healing, or remodeling
3. Unrecognized additional ligament injuries (lateral, posterolateral, or medial collateral) producing deleterious ACL graft loads
4. Unrecognized lower limb malalignment
5. Inadequate rehabilitation and failure to address neuromuscular deficiencies in both lower limbs
6. Postoperative infection

Errors in surgical technique are a leading cause failure of ACL reconstruction [95–98]. We reported a series of 122 knees with failed ACL grafts referred to our center for treatment [14]. A nonanatomic graft placement was found in 107 (88%) knees (Fig. 4.5); 61% of the grafts were located entirely on the intercondylar femoral roof and 35% extended posterior to the ACL tibial attachment. A transtibial technique had been used in 83%. Trojani et al. [98] analyzed the causes of ACL autograft failure in 293 patients who all went on to revision reconstruction. Overall, technical errors at surgery were found in 50% of the cases. Anterior placement of the femoral tunnel was the most common technical problem, occurring in 108 cases (36%). The authors attributed this error to the endoscopic technique and the difficulty in visualization of the preferred femoral tunnel placement. Problems with transtibial (endoscopic) techniques that lead to improper placement of ACL grafts are well recognized. Vertical ACL grafts are able to provide stability to anterior tibial translation, but they are unable to control the combined motions of anterior tibial translation and internal tibial rotation in the pivot-shift phenomenon [14, 15, 99].

Failure to surgically restore deficient lateral, posterolateral, or medial ligament structures has been noted to cause failure of ACL reconstructions due to deleterious graft forces (Fig. 4.6) [100–102]. We previously noted that 25% of 114 consecutive patients requiring ACL revision

Fig. 4.5 Example of a vertical ACL graft orientation on an (**a**) anteroposterior and (**b**) lateral radiograph

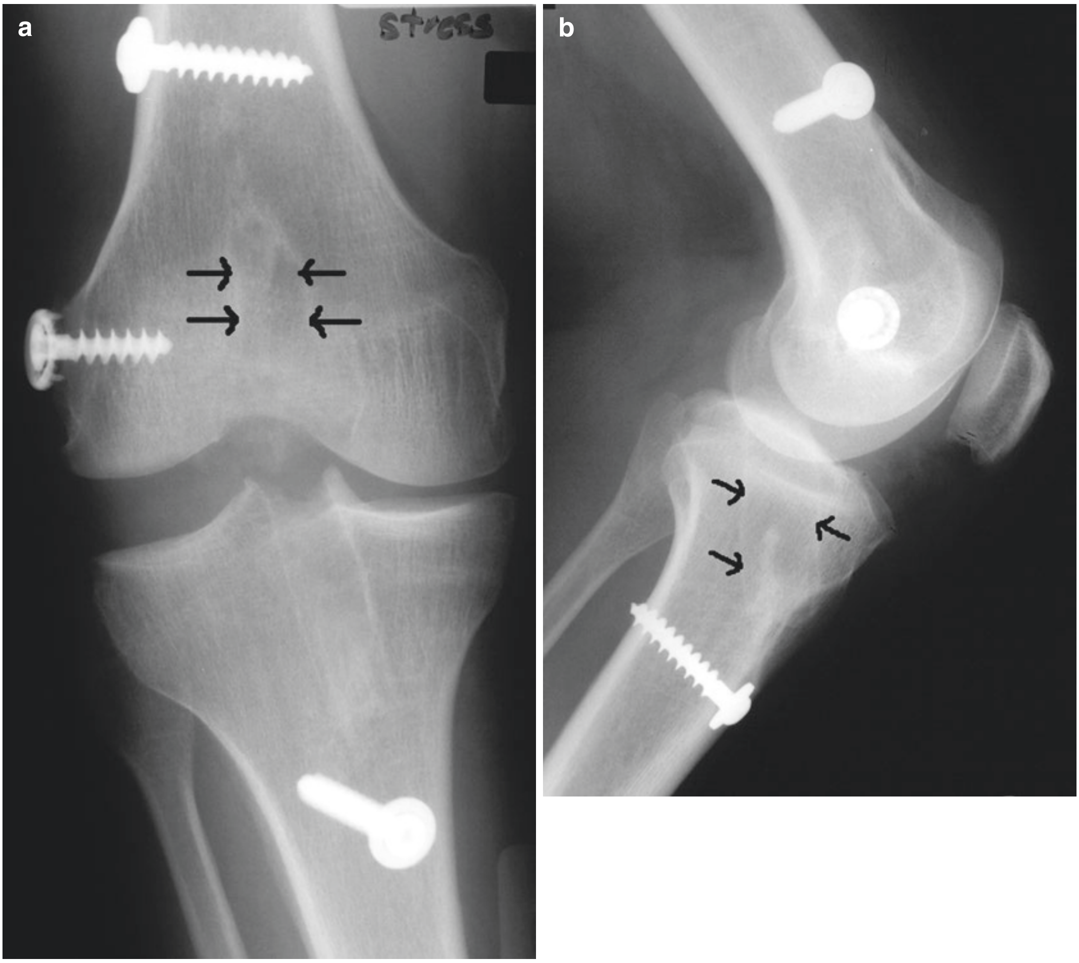

Fig. 4.6 Anteroposterior (**a**) and lateral (**b**) radiographs of a 35-year-old man who presented 5 months after a posterolateral reconstruction with a biceps tendon transfer and an ACL patellar tendon autograft reconstruction for a chronic knee injury. Note the abnormal expansion of both the femoral and tibial tunnels and the vertical orientation of the ACL graft (arrows). The patient presented with failure of both the ACL and posterolateral procedures. (Reprinted from Noyes FR, Barber-Westin SD, Albright JC (2006) An analysis of the causes of failure in 57 consecutive posterolateral operative procedures. Am J Sports Med 34 (9):1419–1430)

reconstruction had uncorrected chronic lateral or medial ligament insufficiency [103]. The ACL graft is subjected to excessive tensile loading under these conditions because of the abnormal medial or lateral tibiofemoral joint opening that occurs with weight bearing. We also reported that 14% of the patients had varus malalignment that had not been corrected before or during the ACL reconstruction, leading to its eventual failure. Varus malalignment also increases tensile forces on ACL grafts due to the shift of the weight-bearing line far into the medial compartment with associated abnormal lateral joint opening due to deficiency of the lateral and posterolateral ligament structures (Fig. 4.7). This is especially true in knees that demonstrate a varus thrust on gait that produces abnormal lateral tibiofemoral joint opening [104, 105] and in triple varus knees with varus recurvatum.

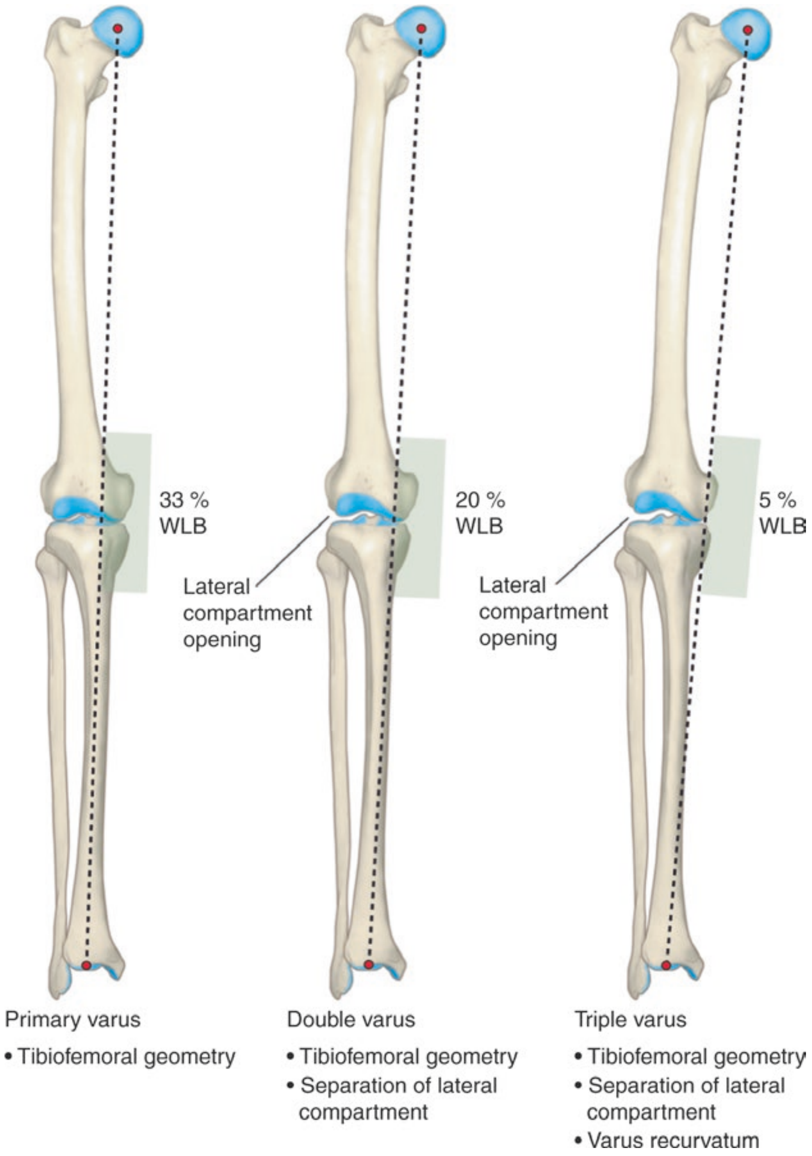

Fig. 4.7 Schematic illustration of primary, double, and triple varus knee angulation. WBL, weight-bearing line. (Reprinted from Noyes FR, Barber-Westin SD (2017): Tibial and femoral osteotomy for varus and valgus knee syndromes: Diagnosis, osteotomy techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 773–847)

Current ACL reconstruction methods do not reproduce the native ACL or its insertion sites [10, 106]. Tendon-to-bone healing must be accomplished in an environment which produces inferior attachments that may result in suboptimal healing [107]. Strategies to promote healing challenges, such as the use of osteoinductive agents and stem cells, are still in the experimental stages and have yet to be proven in long-term clinical studies [108]. Recently, attention has been given to the role of an anterolateral ligament procedure as an augmentation to ACL reconstruction (see also Chap. 1). Some authors have recommended that concurrent ALL reconstruction should be performed with a primary ACL reconstructions in these cases [109, 110], whereas others have stated there is little benefit of this added lateral surgical procedure that may even be deleterious to the joint [111, 112]. Robotic biomechanical studies conducted in our laboratory have demonstrated that the anterolateral structures are not primary restraints for the pivot-shift subluxation event [113]. The ALL reconstruction had no effect on the pivot-shift tests in limiting anterior tibiofemoral translations and had only a modest effect in decreasing ACL graft loads [111]. There appears to be no biomechanical need to perform this added operative procedure except in select instances such as in knees with a grade 3 pivot shift in which a lower-strength ACL graft is used (small STG or allograft) or in revision knees in which the surgeon desires to use a combined intra-articular and extra-articular graft configuration.

Postoperative rehabilitation plays a critical role in returning patients to athletic or demanding occupational activities as safely as possible. We recommend return to play programs that include advanced neuromuscular retraining before patients are released to unrestricted athletics [114–117]. Few studies have assessed the effectiveness of specific rehabilitation protocols in regard to restoring normal muscle strength, balance, proprioception, and other neuromuscular indices required for high-risk activities such as cutting, twisting, and pivoting. Because of the documentation of neuromuscular deficits in the opposite limb, failure to address and fully rehabilitate both knees may be part of the reason for the high reinjury rates in ACL-reconstructed and contralateral limbs.

Once an ACL reconstruction has failed, the outcome of a revision procedure is usually less desirable than primary ACL reconstruction procedures because of higher failure rates, increased symptoms and functional limitations, and eventual joint arthritis [15, 118–120]. 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 [102, 103] 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 damage. These problems led to results that were generally less favorable than those reported following primary operations [15]. For instance, we reported in a study involving 30 patients who received an ACL BPTB autograft reconstruction for acute injuries that 97% had successful restoration of knee stability, 90% rated the overall knee condition as excellent or very good, and 100% had no limitations with daily activities or running, twisting/turning, and jumping/landing [121]. In comparison, in a study of 55 patients who received a revision ACL BPTB autograft [102], 76% had restoration of knee stability, 46% rated the overall knee condition as excellent or very good, and 54% could perform running, twisting/turning, and jumping/landing with few or no problems.

Critical Points

- Errors at surgery with technique, fixation, and choice of graft
- Graft healing issues
- Other ligament deficiencies
- Inadequate rehabilitation
- Postoperative infection

4.7 Salvaging Meniscus Tissue

We have long advocated repair of meniscus tears instead of resection, assuming the appropriate indications are met to preserve function of this vital structure [122–126]. Studies have documented favorable outcomes in knees following meniscus repair compared to meniscectomy [124, 127]. 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
5. Peripheral single longitudinal tears: red-red, one plane, repairable in all cases, and 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
8. Outer-third and middle-third tears (complex, double longitudinal, triple longitudinal, flap): repair versus excision
9. Red-white, multiple planes: repair versus excision

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 indications and contraindications have been discussed in detail elsewhere [124]. The repair uses an accessory posteromedial or posterolateral 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. 4.8). Newer all-inside suture-based meniscus repair devices are now available which are ideal for R/W longitudinal tears and root tears (Fig. 4.9). The postoperative rehabilitation programs allow immediate knee motion and early weight bearing but protect the repairs by not allowing squatting, kneeling, or running for 4–6 months [128].

We have conducted a series of clinical studies to determine the outcome of meniscus repairs at our center [122, 123, 126, 129, 130]. In one study, 198 meniscus repairs in 177 patients were followed 2–9.6 years postoperatively [126]. 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. Although this represented a lower percentage compared with patients who underwent meniscus repair for tears in the peripheral region (typically reported to be ≥90% [124]), we believed it justified the repair of tears in the central zone, especially in patients in aged 21–40 and highly competitive athletes. These results were verified more recently in a systematic review we conducted of 23 investigations in which meniscus repairs for tears in the red-white zone were performed [131]. There were 767 repairs, of which 78% were done with an ACL reconstruction. Overall, 83% of these repairs were considered clinically healed. This acceptable healing rate supports repair of these complex tears under the appropriate indications.

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 [125]. 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-Tesla MRI scanner with cartilage-sensitive pulse sequences was used and T2 mapping were performed. 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,

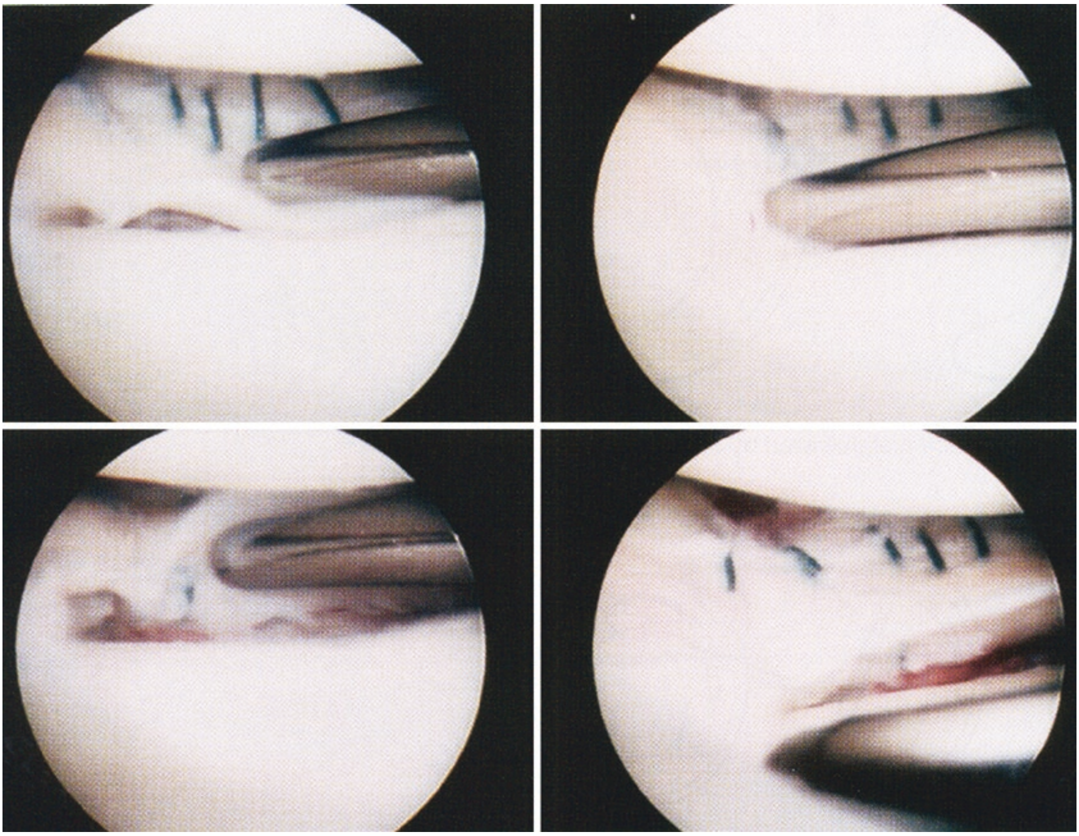

Fig. 4.8 Meniscus repair instead of meniscectomy to preserve knee joint function. A longitudinal meniscal tear site demonstrates some fragmentation inferiorly. This tear required multiple superior and inferior vertical divergent sutures to achieve anatomic reduction. (Reprinted from Noyes FR, Barber-Westin SD (2002) Arthroscopic repair of meniscal tears extending into the avascular zone in patients younger than twenty years of age. Am J Sports Med 30 (4):589–600)

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 (Fig. 4.10).

Critical Points

- We have long advocated repair of meniscus tears when appropriate indications met.
- Recent review 159 studies, 11,711 meniscus tears at ACL reconstruction: 65% meniscectomy; 27%, repair; and 9%, left in situ.
- Meniscus tears suitable for repair located in periphery or middle-third region with blood supply.

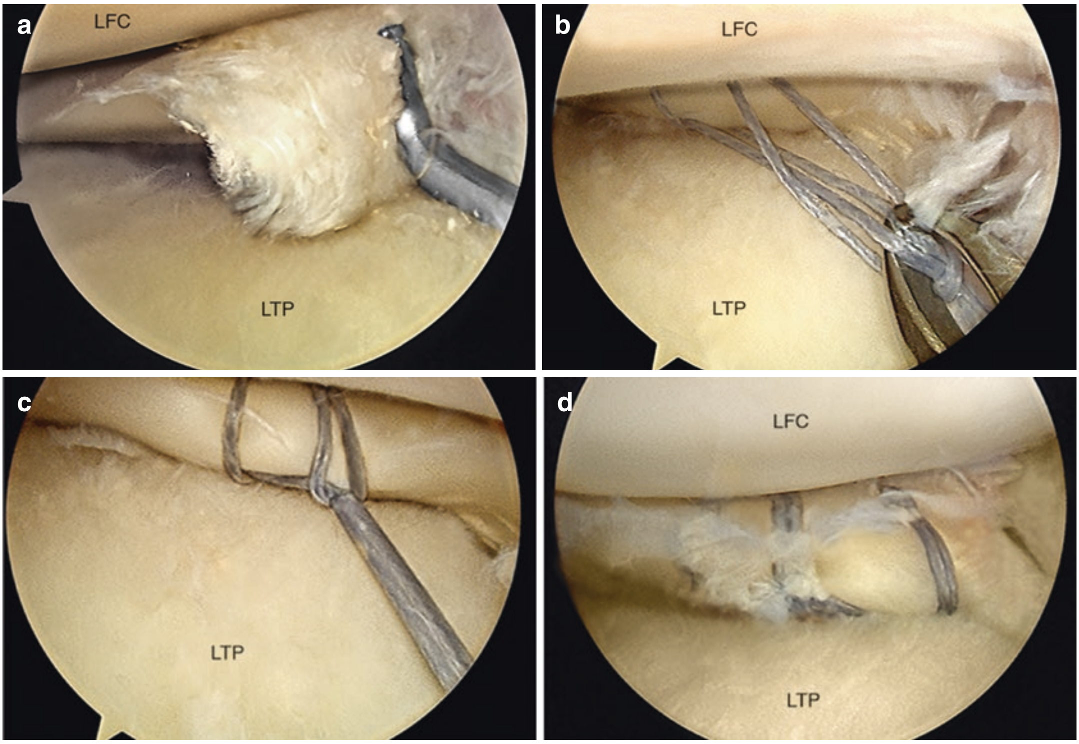

Fig. 4.9 Arthroscopic visualization of a lateral meniscus root tear (**a**). A double locking loop stitch (NovoStitch, Ceterix) is placed through the meniscus at the tear site (**b**). Three loop stitches were used to achieve a high-strength fixation (**c**). Final configuration of the lateral meniscus repair with the meniscus pulled flush to the repair site (**d**). (Reprinted from Noyes FR, Barber-Westin SD (2017) Meniscus tears: diagnosis, surgical techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 677–718)

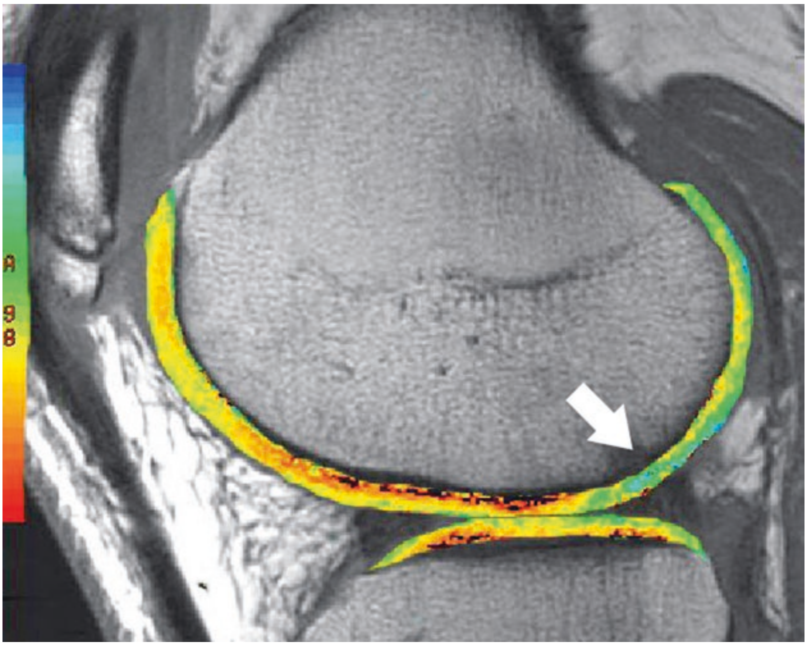

Fig. 4.10 T2 MRI of a 37-year-old male 17 years post-ACL reconstruction and lateral meniscus repair. The patient was asymptomatic with light sports activities. The lateral meniscus repair healed and the ACL reconstruction restored normal stability. Prolongation of T2 values is noted over the posterior margin with adjacent subchondral sclerosis (arrow). (Reprinted from Noyes FR, Chen RC, Barber-Westin SD et al. (2011) Greater than 10-year results of red-white longitudinal meniscal repairs in patients 20 years of age or younger. Am J Sports Med 39 (5):1008–1017)

- Meticulous vertical divergent suture technique favored, multiple sutures passed through superior and inferior surfaces of meniscus.
- 198 repairs followed 2–9.6 years: 80% asymptomatic.
- 30 repairs (patients ≥40 years old) followed 2–6 years: 87% asymptomatic.
- 29 repairs (patients ≤20 years old) followed 10–22 years: 62% normal, nearly normal characteristics.

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Part II

Proposed Risk Factors of Noncontact ACL Injuries

The Role of Shoe-Surface Interaction and Noncontact ACL Injuries

5

Ariel V. Dowling and Thomas P. Andriacchi

Abstract

This chapter discusses the role of shoe-surface interaction with regard to the risk of noncontact ACL injuries in female athletes. Shoe characteristics such as the number, diameter, length, and placement of cleats are described relative to the role they may play in ACL injuries. The effect of playing surface characteristics is described for different types of grasses and artificial turfs. Climate conditions potentially affecting ACL injury rates are summarized. Biomechanical adaptations to shoe-surface interactions and environmental factors are discussed relative to increasing the risk of noncontact ACL injuries.

5.1 Introduction

One of the most prominent environmental factors affecting a female athlete's risk of noncontact anterior cruciate ligament (ACL) injury is shoe-surface interaction. The shoe-surface interaction is defined by the force of the friction between the athlete's shoe and the surface on which she is moving. Friction force is the force that resists the relative motion of two surfaces sliding against one another. Friction force is governed by the following equation:

$$F_{\text{friction}} = \mu \times F_{\text{normal}}$$

where μ is the coefficient of friction (COF), an empirical property of the two surfaces, and F_{normal} is the net perpendicular (or normal) force compressing the two surfaces together. COF is used to quantify the shoe-surface interaction because it is an empirical property of the two surfaces; e.g., the COF between rubber-soled shoes and wood floor will be the same regardless of the size of the shoe or the weight of the athlete because the COF is defined by the properties of the rubber and the wood.

Changing the COF of the shoe-surface interaction causes athletes to alter their movement techniques in order to accommodate for the change in the COF. Movement alterations lead to changes in biomechanics, which can affect an athlete's risk of ACL injury. Therefore, in order to understand the role of the shoe-surface interaction with respect to noncontact ACL injuries, it is important to discuss the factors that affect the COF since these factors ultimately influence the athlete's biomechanics and risk for injury. There are three factors that can affect the COF of the shoe-surface interaction: the intrinsic shoe properties, the intrinsic surface properties, and the weather conditions during the time of play.

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Furthermore, research has suggested that there is a relationship between the COF and the rate of ACL injury; an increased COF of the shoe-surface interaction may lead to an increased incidence of ACL injury [1–9]. Increased COF conditions (sparse, narrow, long cleats, artificial turf and rubber surfaces, hot and dry weather) is associated with higher ACL injury rates compared to decreased COF conditions (numerous, wide, short cleats, natural surfaces, cold and wet weather). Studies have also shown that increasing the COF of the shoe-surface interaction causes an athlete to alter movement techniques in specific ways that may increase risk of ACL injury, providing a biomechanical basis for the increased incidence of ACL injuries observed on high COF surfaces.

Unfortunately, the majority of the studies describing the role of the shoe-surface interaction in noncontact ACL injuries have been conducted with exclusively male subjects or a combination of male and female subjects without performing a gender comparison. However, because shoe-surface interaction is an extrinsic, environmental factor, many of the conclusions from these studies apply to female athletes even if the research did not conduct a gender comparison. As such, this chapter will discuss all prior research (regardless of gender) in order to fully investigate how the shoe-surface interaction affects noncontact ACL injuries. When available, studies conducted with female athletes will be highlighted, and these results will be compared to the male-only and gender-neutral studies.

Critical Points

- Shoe-surface interaction characterized by coefficient of friction (COF).
- Primary factors affecting COF: shoes, surfaces, and weather.
- Increased COF may lead to increased incidence of ACL injury.
- Biomechanical adaptations to increased COF increase risk for ACL injury.
- Majority of research focused on male athletes.

5.2 Shoe Characteristics

Footwear has a significant effect on noncontact ACL injuries because it alters the fixation of the foot to the surface. Shoes with protruding cleats or studs (known colloquially as cleats) are the primary footwear used in sports associated with higher ACL injury rates. Cleated shoes vary based on two components: the characteristics (number, diameter, and length) and placement of the cleats. Different sports have adopted cleat styles that are optimized for athletes participating in that particular sport (e.g., football cleats versus soccer cleats versus baseball cleats); however, the official shoe regulations for each sport allow for a wide range of acceptable styles. There are three general categories of cleated shoes: conventional American football cleats (Fig. 5.1, cleats A and B), soccer cleats (Fig. 5.1, cleats D and E, Fig. 5.2, flat cleats, Fig. 5.3, cleats A and B), and turf cleats (Fig. 5.3, cleats D). Overall, shoes that have sparse, narrow, and long cleats placed at the periphery of the shoe sole will have greater COF than shoes with numerous, wide, and short cleats equally distributed on the shoe sole.

5.2.1 Cleat Characteristics: Number, Diameter, Length

The largest variation between different models of cleated shoes is the characteristics of the cleats on the sole of the shoe. Models may vary in terms of the total number of cleats, diameter of the tip of the cleat, and total length of the cleat. Overall, modern American football cleats usually contain the fewest number (varying from 7 to 11 cleats total) that are 3/8″ in diameter and up to 1/2″ in length. Soccer cleats have 14–15 cleats that are 3/8″ in diameter and length, while turf cleats may contain up to 100 small cleats that are just 1/4″ in diameter and length.

Research has shown that the total number, tip diameter, and length of the cleats may affect ACL injury rates because shoes with fewer, narrower, and longer cleats result in an increased incidence. In 1971, Torg and Quedenfeld [10] conducted one of the first major studies that

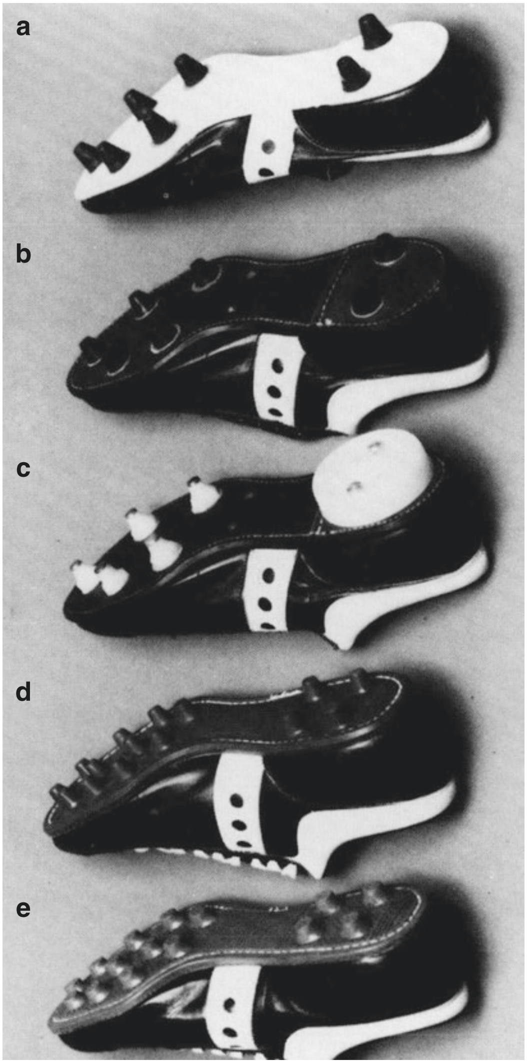

Fig. 5.1 Cleat models tested by Torg et al. [9] (**a**) Group I prototype, conventional seven posted football shoe with 3/4″ cleats. (**b**) Group II prototype, conventional seven posted football shoe with 1/2″ cleats. (**c**) Group III prototype, conventional football shoe with Bowdoin heel and five 3/4″ cleats. (**d**) Group IV prototype, "soccer type" shoe with 15 cleats, 1/2″ long with 3/8″ cleat tip diameter. (**e**) Group V prototype, "soccer type" shoe with 15 cleats, 3/8″ long with 1/2″ cleat tip diameter (Reprinted from Torg et al. [9]; with permission of SAGE Publications, Inc.)

investigated the relationship between cleat characteristics and injury rates. Differences in knee injury rates were determined on natural grass between male high school American football players using the standard football cleats of the era (7 total cleats, conical cleats, 3/4″ length) versus players using soccer cleats (14 total cleats, 1/2″ diameter, 3/8″ length). A significant decrease was reported in the incidence and severity of knee and ankle injuries for the players using the soccer cleats. On the basis of this study, the authors recommended that the standard football cleats of the era be banned because they were "a major factor responsible for the epidemic of knee injuries" in football when compared to the soccer cleats [10]. The authors further recommended that new models of football cleats should be required to contain a minimum of 14 cleats with a minimum cleat tip diameter of 1/2″ and a maximum length of 3/8″, similar to the less-injurious soccer cleats.

Further research suggested that the reason shoes with fewer, narrower, and longer cleats caused a greater incidence of ACL injury is because these shoes create a higher COF with the playing surface, especially in rotational movements. In a set of experiments, Torg et al. [9] measured the torque required to release the shoe-surface interaction (defined as the release coefficient) using a variety of cleat types and surfaces. In this study, the release coefficient was analogous to the COF of the shoe-surface interaction in rotation. Twelve shoe models were classified into five groups based on cleat characteristics: (A) standard American football cleats with 3/4″ length cleats, (B) standard American football cleats with 1/2″ length cleats, (C) standard American football cleats with 3/4″ length cleats and a modified disk on the heel, (D) soccer cleats with 1/2″ length and 3/8″ diameter cleats, and (E) soccer cleats with 3/8″ length and 1/2″ diameter cleats (Fig. 5.1). On natural grass, the release coefficient was greatest for group A (0.55), followed by group B (0.44), group C (0.37), group D (0.36), and group E (0.28). These results suggest that as cleats become more numerous, shorter, and wider, the release coefficient (and therefore the COF) required to release the shoe-surface interaction decreases. Furthermore, the American football cleats had significantly greater release coefficients than the rest of the shoe models in the study. As such, the greater incidence of injury observed in the first study by Torg [10] for players wearing American football cleats was

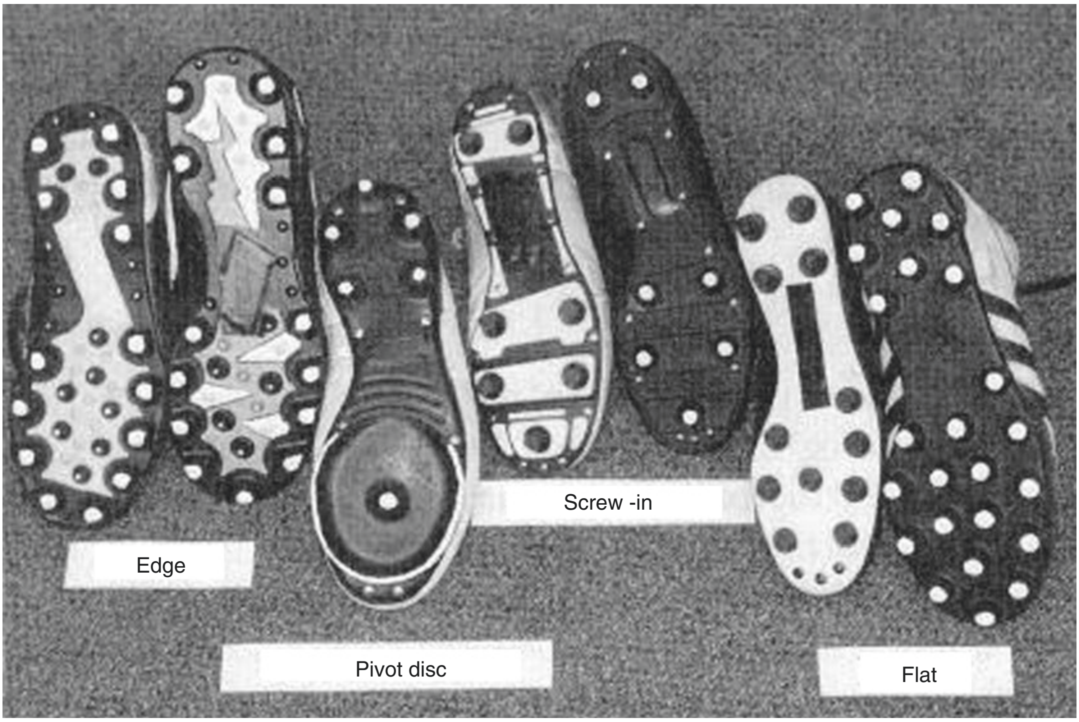

Fig. 5.2 Cleat models tested by Lambson et al. [1] Four American football cleat designs evaluated for torsional resistance and rate of ACL injuries (Reprinted from Lambson et al. [1]; with permission of SAGE Publications, Inc.)

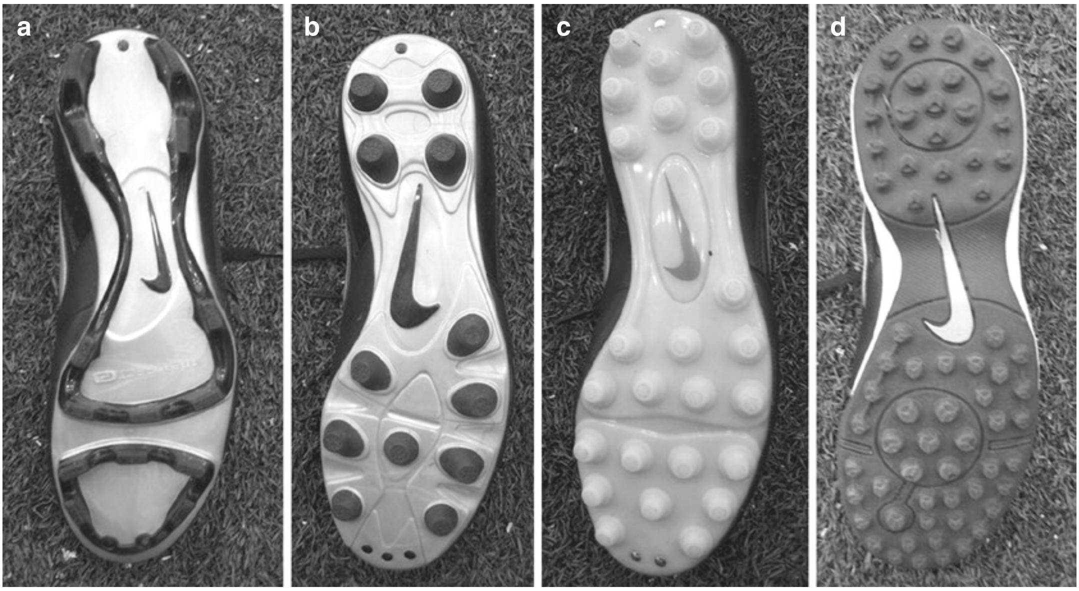

Fig. 5.3 Cleat models tested by Queen et al. [44] Configurations of the four Nike Vitoria cleat types: (**a**) bladed, (**b**) firm ground, (**c**) hard ground, and (**d**) turf cleat (Reprinted from Queen et al. [44]; with permission of BMJ Publishing Group Ltd.)

most likely a result of increased COF created by the cleats.

These results were confirmed in a later study by Heidt et al. [11], who also determined that peak rotational torque decreased as the cleats become more numerous, shorter, and wider. In this investigation, 15 different models of shoes were tested for peak rotational torque on a variety of natural and artificial surfaces. The shoe models were split into five groups: turf cleats, soccer cleats, standard American football cleats, and court shoes (basketball-like shoes with no cleats on the sole). On grass, all five groups of shoes were significantly different from each other in terms of peak rotational torque. The standard American football cleats had the highest peak rotational torque (42.6 Nm), followed by soccer cleats (31.0 Nm), turf cleats (14.1 Nm), and court shoes (11.8 Nm). In a separate study by Villwock et al. [12], ten models of cleats (five different groups) were tested on a variety of natural and artificial surfaces. Across all surfaces, the turf cleats exhibited a significantly decreased peak rotational torque (69.9 Nm) when compared with the rest of the cleat groups (Table 5.1). This investigation showed that turf cleats, which have numerous very short cleats, had a lower COF for the shoe-surface interaction.

5.2.2 Cleat Placement

The placement of the cleats on the sole of the shoe can also affect ACL injury rates. In general, cleats are either evenly distributed on the forefoot and heel of the shoe or are placed around the edge of the sole, with only a few cleats on the inside. In a seminal investigation, Lambson et al. [1] conducted a 3-year prospective study to evaluate how the torsional resistance and the incidence of ACL injury vary based on cleat placement in over 3000 high school American football players. Four groups of cleats were used: (1) edge cleats, with long irregular cleats at the periphery of the sole and small short cleats in the middle; (2) flat cleats, with homogenously short cleats (soccer cleats); (3) screw in cleats, with 7 0.5″ long cleats; and (4) pivot disk cleats, with a 10 cm circular disk centered around one cleat on the forefoot (Fig. 5.2) [1]. The researchers determined that the edge cleats were associated with a significantly higher rate of ACL injury (0.017%) than the other three cleat groups combined (0.005%). The edge cleats also produced significantly higher torsional resistance on both artificial turf and natural grass when compared to the other cleat groups, showing that these cleats create a higher COF of the shoe-surface interaction [1]. This result was confirmed by Villwock et al. [12], who determined that one of the models of the edge cleats tested in their study resulted in significantly higher rotational stiffness than the other cleat models. Altogether, these results suggest that edge cleats create a higher COF with the surface and are also associated with an increased rate of ACL injury.

5.2.3 Male Focus

Unfortunately, all of the major studies on shoe characteristics that affect COF and ACL injury have been conducted on male athletes, specifically American football players. One reason for this disparity might be the era during which the research was conducted. The studies by Torg et al. [9, 10] were completed in the early 1970s, which was a time when women did not compete in sports in large numbers and the most dominant sport for men in the United States was American football. As such, a study that included female athletes would have been much more difficult to complete. Furthermore, most of the studies have focused on comparing different cleat models. Since the seven-cleat model is almost exclusively used by American football players, any study that focused on a comparison with this cleat model would be required to study American football. The vast majority of both male and female soccer players wear similar models of soccer cleats, so a comparison in footwear with this population is more difficult. However, many of the conclusions from the studies in male athletes can be extrapolated to female athletes because the design of cleats for men and women is similar in terms of cleat characteristics, and many women use men's

Table 5.1 Mean peak torques (N·m) for ten cleated football shoe models tested on four playing surfaces [12]

	12 studded		Edge			Hybrid		7 studded		Turf	
Surface	Blade II	7 Fly	Vapor	TRX	Blitz	Superbad	Grid Iron	Blade D	Quickslant	Turf Hog	Mean ± SD across surfaces
FieldTurf	135.8	120.4	131.6	129.0	121.8	117.4	112.4	119.6	113.4	81.4	118.3 ± 15.2*
Astroplay	121.6	107.8	118.4	117.0	109.2	119.8	109.6	130.8	105.8	78.4	111.8 ± 14.5*
Grass, sand based	115.6	107.4	100.4	98.6	74.2	101.4	84.8	112.4	104.6	59.6	95.9 ± 18.0**
Grass, native soil	87.6	95.0	98.6	79.8	77.8	73.6	81.4	83.0	94.4	60.0	83.1 ± 12.3**
Mean ± SD across shoes	115.2 ± 19.3	107.7 ± 10.9	112.3 ± 14.9	106.1 ± 20.1	95.8 ± 21.2	103.1 ± 19.4	97.1 ± 15.3	111.5 ± 19.4	104.6 ± 8.8	69.9 ± 11.0***	

SD standard deviation

*Significant difference from natural grass surfaces ($P < 0.001$)

**Significant difference from all other surfaces ($P = 0.008$)

***Significant difference from all other shoe models ($P < 0.001$)

Blade II TD (Nike), Scorch 7 Fly (Adidas), Vapor Jet TD (Nike), Scorch TRX (Adidas), Corner Blitz 7 MD (Adidas), Air Zoom Superbad FT (Nike), Grid Iron (Adidas), Air Zoom Blade D (Nike), Quickslant D (Adidas), Turf Hog LE (Adidas) cleats for sports. More research needs to be conducted to accurately determine the effects of cleat characteristics on female athletes.

Critical Points

- Cleats most common form of footwear during ACL injurious sports.
- Primary cleat characteristics: number, diameter, and length.
- Cleat models with fewer, narrower, and longer cleats result in increased ACL injuries because these cleats increase COF of the shoe-surface interaction.
- Edge cleats, with cleats placed around the periphery of the shoe sole, increase ACL injury rates due to increased COF of the shoe-surface interaction.
- Most cleat research on male athletes but may apply to female athletes.

5.3 Surface Characteristics

The playing surface has a significant effect on noncontact ACL injuries because it alters the grip of the athlete's feet during movement. There are four categories of surfaces used for sporting events: natural grass, artificial turf, wood floor, and artificial rubberized floor. While variations exist between the surfaces encompassed by each category, artificial turf is especially variable. Artificial turf may be further subdivided by age of installation into first-, second-, third-, or fourth-generation turf. Artificial rubberized floor is not a common surface in the United States but is frequently used for sports such as team handball and floorball, which are popular in European and Scandinavian countries (Fig. 5.4).

For sports that may be played outdoors or indoors (such as soccer, Australian and American

Fig. 5.4 Team handball played on an artificial rubberized floor. Reprinted by permission of user Ahodges7 http://en.wikipedia.org/wiki/File:Team_Handball_Jumpshot_09_USA_Nationals.JPG

football), the two primary surfaces are natural grass and some variation of artificial turf. For sports that are only played indoors (such as basketball, team handball), the two primary surfaces are wood floor and artificial rubberized floor. In general, artificial turf has a higher COF than natural grass, and artificial rubberized floor has a higher COF than wood floor.

5.3.1 Grass Varieties

Different grass types may alter the incidence of noncontact ACL injury. A study of grass types used in major venues for the Australian Football League from 1992 to 2004 determined that Bermuda (couch) grass, as opposed to rye grass, was associated with a significantly higher ACL injury rate [4]. The relative risk for ACL injury on Bermuda (couch) grass compared to other grass surfaces was 1.7. The authors suggested that the increased thatch (Fig. 5.5) in the Bermuda (couch) grass increased the "trapping" of the athletes' cleats, thereby increasing the COF between the grass and the shoe [4]. As such, the results from this study show that grass variations that create a higher COF with the surface are associated with an increased rate of ACL injury.

5.3.2 Artificial Turf

Artificial turf has evolved significantly since it was first introduced in the 1960s. The first version of artificial turf, known as first generation, consisted of stiff, short (10–12 mm), high-density nylon fibers sewn into a shock pad and resembled woven carpet (Fig. 5.6). These fields

Fig. 5.5 Grass varieties tested by Orchard et al. [4] (**a**) Bermuda (couch) grass surface, showing thick thatch layer between grass leaves and soil. (**b**) Kikuyu grass, also showing thick thatch later. (**c**) Rye grass surface, showing minimal thatch layer. This is probably a safer surface than the others, as the blades or cleats of the football boot are less likely to be "gripped" by the surface. (**d**) Annual blue grass surface, showing moderate thatch layer (Reprinted from Orchard et al. [4]; with permission of BMJ Publishing Group Ltd.)

were coarse and could cause significant friction burns and blisters to the players [13]. AstroTurf was the first commercial brand of artificial turf to be installed in stadiums and arenas on a wide scale, and the original product developed in 1965 is considered the prototype of first-generation artificial turf. Second-generation artificial turf, introduced in the late 1970s and early 1980s, consisted of lower density, longer (20–35 mm) fibers made from polypropylene [13]. Furthermore, sand was used to fill in the space between the fibers (known as infill) in order to provide stability and greater cushioning for the athletes (Fig. 5.7) [14]. Third-generation artificial turf was introduced in the 1990s. This turf had long (35–65 mm), widely spaced fibers made from soft polyethylene, and the infill consisted of sand covered by rubber granules [13]. The combination of sand and rubber provided stability and elasticity, which allowed athletes wearing cleats to "dig" into the surface for traction (Fig. 5.8). The most recent fourth-generation artificial turf contains improvements such as different mixes of infill materials, long (up to 80 mm) and soft fibers, and variable fiber density [13]. Recent innovations in materials and construction have enabled manufacturers to create artificial turf that can replicate many of the positive properties of natural grass.

Because of the variations in artificial turf over the years, research studies investigating artificial turf have reported conflicting results based on which type of turf was tested. As such, investigations are grouped into two broad categories: first-

Fig. 5.6 First-generation artificial turf. 10–12 mm fiber length, integral shock pad, nylon, unfilled, hard, and abrasive. Developed in the 1960s [13] (Reprinted by permission of Loughborough University)

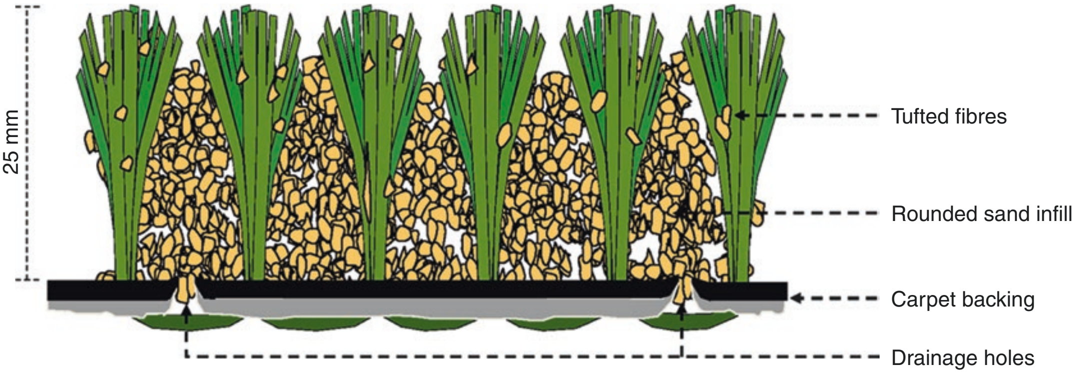

Fig. 5.7 Second-generation artificial turf. 20–35 mm fiber length, monofilament or fibrillated polypropylene, wider spaced tufts, and rounded sand infill [14]. Developed in the late 1970s, initially without a shock pad. Banned in the 1980s by United Kingdom professional soccer for being unplayable [13] (Reprinted by permission of Taylor & Francis)

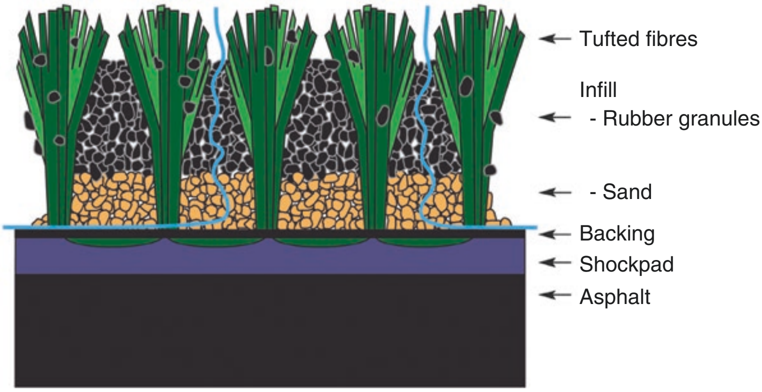

Fig. 5.8 Third-generation artificial turf. 40–65 mm fiber length (long pile), monofilament/fibrillated fibers, with sand/rubber infill. Developed in the late 1990s [13] (Reprinted by permission of Sheehan)

and second-generation artificial turf and third- and fourth-generation artificial turf. Overall, research suggests that there was a higher ACL injury rate on first- and second-generation artificial turf surfaces compared with natural grass; however, the injury rates are comparable between third- and fourth-generation artificial turf surfaces and natural grass [15–17].

5.3.3 First- and Second-Generation Turf

Studies that focused on first- and second-generation artificial turf surfaces found a significantly higher incidence of ACL injury on these surfaces compared to natural grass. Many of these studies were conducted using American football players. A 9-year study (1980–1989) of injury rates in the National Football League (NFL) found a significantly higher ACL injury rate on AstroTurf (first generation) compared to natural grass for special teams play [7]. In 1988, Nigg and Segesser [18] concluded that there was a definite increase in minor knee injuries and a possible increase in severe injuries on first- and second-generation artificial turf compared to grass in American football. Furthermore, in 1990, Skovron et al. [19] determined there was a 30–50% greater risk for knee injury on first- and second-generation artificial turf compared to natural grass for American football players.

Outside of American football, similar results were observed for elite Icelandic male soccer players. Arnason et al. [20] reported a higher injury rate on first- and second-generation artificial turf compared to both natural grass and gravel in these athletes. Youth soccer players also exhibited an increased incidence of injury on older artificial surfaces; one study in 1986 found a sixfold increase in the number of injuries reported for indoor soccer (played on surfaces like artificial turf or wood flooring) versus outdoor soccer (played on natural grass) [21].

Unfortunately, few studies have been conducted on the effects of first- and second-generation artificial turf versus natural grass for female athletes, most likely because females had significantly lower participation in sports during these decades. However, one study suggests that older artificial surfaces caused more injuries for female athletes when compared to natural grass. A small study of women's field hockey in 1984–1985 examined the rates and types of injuries during the Australian National Championships when the games were played on AstroTurf (first generation) versus grass [22]. The study determined that the overall lower limb injury rates were higher on the AstroTurf. However, when the lower limb injury rates were compared by type of injury, soft-tissue injuries occurred more frequently on AstroTurf while joint injuries occurred more frequently on grass.

For American football and other sports, it has been hypothesized that the greater incidence of ACL injury reported on first- and second-generation artificial turf surfaces was related to the higher COF of these artificial surfaces [3].

Lambson et al. [1] tested 15 different cleat models on both artificial turf and natural grass. For all cleat models, the peak rotational torque was greater on the artificial turf. Livesay et al. [23] tested both traditional soccer cleats and turf cleats on five different surfaces: natural grass, AstroTurf (first generation), two types of Astroplay (third generation), and FieldTurf (third generation). For the traditional soccer cleats, the peak rotational torque on all the artificial surfaces was significantly greater than natural grass (Fig. 5.9). For the turf shoe, the peak torque on the AstroTurf and FieldTurf was greater than the natural grass (Fig. 5.10) [23]. These results were confirmed by Villwock et al. [12], who compared five models of American football cleats on four surfaces: AstroTurf (first generation), FieldTurf (third generation), and two types of natural grass. This study determined that for all the cleat models tested, AstroTurf had the highest peak rotational

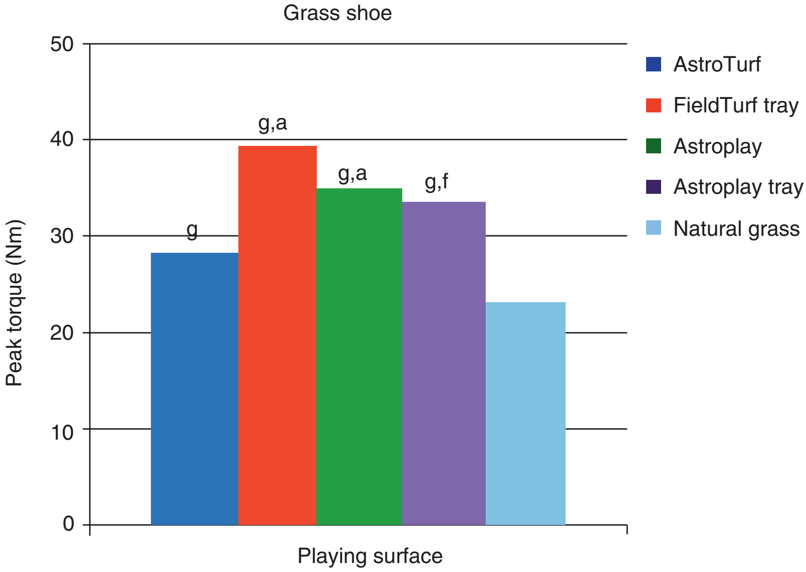

Fig. 5.9 Mean peak torques for the grass shoe across all playing surfaces under a compression load of 333 N; *g* signifies a significant difference from grass; *a*, i signifies a significant difference from AstroTurf, *f* signifies a significant difference from FieldTurf tray [23]

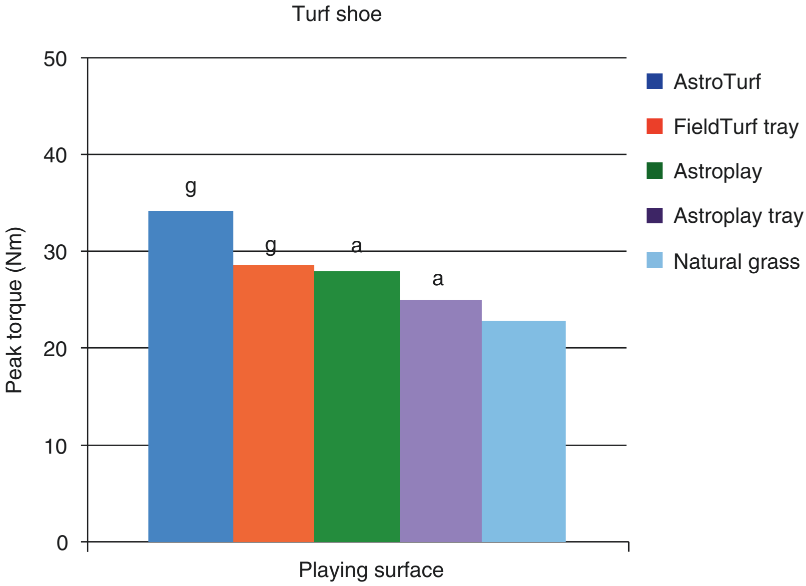

Fig. 5.10 Mean peak torques for the turf shoe across all playing surfaces under a compression load of 333 N; *g* signifies a significant difference from grass, *a* signifies a significant difference from AstroTurf, *f* signifies a significant difference from FieldTurf tray [23]

torque (118.3 Nm), followed by FieldTurf (111.8 Nm), and natural grass surfaces (94.9 Nm and 83.1 Nm). All four surfaces were statistically different from each other.

However, some studies have not observed a difference between the COF of first- and second-generation artificial surfaces and natural grass. Torg et al. [9] compared the release coefficients for various cleat models on three types of first- and second-generation artificial surfaces: AstroTurf, Tartan Turf, and PolyTurf. This study determined that for each cleat model tested, the release coefficients for the three artificial surfaces were generally the same as the grass surface. Heidt et al. [11] tested five models of American football cleats on first-generation AstroTurf and grass. For all the cleat models combined, there was no difference in the mean peak rotational torque on AstroTurf compared to grass (20.33 Nm versus 23.56 Nm). Differences in methodology, testing equipment, and cleat models may account for the disparities observed between these studies and other investigations.

Finally, cadaveric studies have shown that the strain in the ACL is greater during rotational loading on first-generation artificial surfaces than on natural grass. In one study, a standardized rotational moment was applied to eight cadaveric specimens placed on AstroTurf (first generation), modern playing turf (third generation), and natural grass [24]. Strain was measured from a strain gauge affixed to the ACL. For the same applied force and moment, the average maximum strain in the ACL was significantly less on the grass surface compared to the two artificial surfaces, while the maximum load measured at the foot was observed on the AstroTurf surface. These results suggest that for high COF, AstroTurf produces not only greater rotational torque, but increased intra-articular pressure at the knee might compared to natural grass.

5.3.4 Third- and Fourth-Generation Turf

More recent studies of third- and fourth-generation artificial turf have observed that the rates of knee injuries are comparable between these surfaces and natural grass [16]. In two prospective studies, FieldTurf (third generation) was associated with similar overall rates of injury for American high school football players [25] and collegiate football players during game situations [26]. Elite European soccer players also exhibited similar injury rates between third-generation artificial turf and natural grass during the 2002–2003 season [27].

Injury rates of female athletes on third- and fourth-generation artificial turf have also been reported. Steffen et al. [28] conducted an investigation of young female soccer players and newer generations of artificial turf. A total of 2020 athletes from 109 teams were followed for 8 months during the 2005 season. The overall risk of acute injuries was similar between third-generation artificial turf and natural grass. However, the incidence of serious injuries during games (as opposed to practices) was significantly higher on artificial turf than grass. The number of noncontact ACL injuries in this study (6) was not large enough for statistical significance. Other extensive studies by Fuller et al. [29, 30] compared the injury rates of male and female collegiate soccer players over two seasons on newer generation artificial turf versus natural grass using the National Collegiate Athletic Association (NCAA) Injury Surveillance System. The researchers concluded that (for both male and female athletes) there were no major differences in the incidence, severity, nature, or cause of injuries between newer generations of artificial turf and natural grass during either games or practices. When analyzed specifically for ACL injuries among females, there were no significant differences in the incidence of injury between the different surfaces. During games, the incidence of injury (per 1000 player-hours) was 1.29 for artificial turf and 1.65 for grass. The percent of noncontact ACL injuries was 33% (3/9) on artificial turf and 38% (22/58) on grass [29]. During practices, the incidence of injury (per 1000 player-hours) was 0.02 for artificial turf and 0.09 for grass [30].

Other studies on male and female youth players have yielded similar results for newer generations of artificial turf. Soligard et al. [31] studied injury rates among youth soccer players in

Norway from 2005 to 2008. This study determined that there was no overall greater rate of acute injury among either male or female soccer players on third-generation artificial turf than natural grass. In terms of knee injury, the incidence rate for the entire population (male and female, per 1000 player-hours) was 4.6 on artificial turf and 5.6 on grass. Aoki et al. [32] also reported that there was no difference in the incidence of acute injury for male youth soccer players on newer generation artificial turf versus natural grass.

The COF of newer generations of artificial turf has not been extensively studied, especially for the most recent turf variations. The studies described previously suggest that some surfaces may be similar to grass, while others may be similar to older generations of artificial turf. Livesay et al. [23] determined that soccer cleats on Astroplay and FieldTurf (both third generation) had greater peak rotational torque than the same cleats on grass and AstroTurf (Fig. 5.9). For the turf cleats, only FieldTurf had greater peak rotational torque than grass, and Astroplay had less peak rotational torque than AstroTurf (Fig. 5.10). Villwock et al. [12] determined that, for 15 cleat models tested, FieldTurf had less peak rotational torque than AstroTurf but more peak rotational torque than two different natural grass surfaces (Table 5.1). The conflicting results suggest that the decreased incidence of injury observed on newer artificial surfaces might be a result of multiple factors, such as the COF of the surface as well as the physical composition of the surface (fiber materials, infill construction, etc.). More research is necessary to illuminate the relationship between newer generations of artificial turf, COF, and the incidence of noncontact ACL injury in female athletes.

5.3.5 Artificial Rubber Floors

Artificial rubberized flooring may also cause a significant increase in the incidence of ACL injury. In 1998, injury surveillance in the Australian Army determined that there were six unexpected ACL injuries within a 12-month period [33]. An investigation determined that the source of these injuries was newly installed rubber matting on an obstacle course, as all the injuries occurred as the recruits landed or twisted on the matting [33]. The authors suggested that the cause of the injuries was excessively high COF between the rubber matting and the rubber soles of the recruits' boots. A subsequent analysis of the injuries confirmed that the addition of the rubber matting was the source of the injuries, as there were no ACL injuries reported prior to the installation of the rubber matting or after the matting had been removed [34].

Female athletes may also have a greater risk for ACL injury on rubberized flooring than male athletes. From 1989 to 2000, Olsen et al. [2] studied the incidence of ACL injury for both male and female elite Norwegian handball players on wooden floors (lower COF) compared to artificial rubberized floors (higher COF). The female athletes suffered a total of 36 ACL injuries (0.96 per 1000 player-hours) on the artificial rubber floor versus 8 (0.41 per 1000 player-hours) on the wood floor, which was statistically significant ($P = 0.03$). For men, there was no significant difference in the incidence rate for rubber versus wood floor (0.20 and 0.32 per 1000 player-hours, respectively). This study concluded that the ACL injury rate for females was more than twofold higher on the artificial rubber floors than on the wooden floors, indicating that the risk for injury on rubber floors is disproportionately greater for women. Furthermore, Pasanen et al. [6] compared the incidence of injury for female Finnish floorball players between artificial rubberized floors and wooden floors in a single season prospective study. The ACL injury rate (per 1000 player-hours) on the artificial rubberized floor was 5.0 compared to 2.1 for wood floor. The authors suggested that the reason for the significantly higher injury rate was the increased shoe-surface interaction of the artificial rubberized floor.

No studies have quantified the peak rotational torque or release coefficient for artificial rubberized floor. However, a rubber-rubber surface interaction creates a large COF [35, 36]. This type of interaction is common on artificial rubberized floor, as most athletes wear athletic shoes with rubber soles when competing on this surface.

Therefore, it is highly likely that the COF of the rubberized floor is significant and may be the cause of the observed increase in ACL injury among female athletes on this surface.

5.3.6 Artificial Surfaces and Female Athletes

The investigations on third- and fourth-generation artificial turf as well as artificial rubberized surfaces suggest that female athletes might be more affected by changes in the surface characteristics. While most studies on third- and fourth-generation artificial turf found no differences between male and female athletes, Steffen et al. [28] did find a significant increase in serious injuries that occurred during game situations for young female athletes. Furthermore, the studies that investigated the effects of artificial rubberized floor on ACL injury rates determined that females have significantly greater ACL injury rates on these surfaces when compared to males. However, why rubber floor affects females more than males is unknown. Additional research is necessary in order to understand the cause of the difference in ACL injury rates between men and women on rubber floors. Until then, female athletes should exercise caution when competing on this surface.

Critical Points

- Outdoor sports are played on grass (low COF) or artificial turf (high COF). indoor sports are played on wood (low COF) or rubber floor (high COF).
- Grass with increased COF results in greater ACL injury rates.
- First- and second-generation turf have increased incidence of ACL injury and increased peak rotational torque compared to grass.
- Third- and fourth-generation turf have equal incidence of ACL injury and variable peak rotational torque compared to grass.
- Rubber flooring has high ACL injury rates and high COF compared to wood.
- Female athletes have high risk of ACL injury on rubber floors vs. wood but comparable risk for newer generations of artificial turf vs. grass.
- More research required to determine why females have a greater risk of injury on rubber floors.

5.4 Weather

The weather can also affect the incidence of ACL injury because it alters the characteristics of the shoe-surface interaction. The weather affects the shoe-surface interaction in two ways: the water content of the surface and the temperature of the shoe-surface interaction. The water content of the surface changes based on the amount of rainfall and evaporation, and the temperature changes based on the season. Overall, wet and cold conditions create a low COF of the shoe-surface interaction, while dry and warm conditions create a high COF.

5.4.1 Water Content of Surface

Previous research has shown that there is an increased incidence of ACL injury during dry conditions (low rainfall and high evaporation) compared to wet conditions (abundant rainfall and low evaporation). A study in the Australian football league from 1989 to 1993 found that 92.5% of the observed ACL injuries occurred during dry conditions as opposed to wet conditions [8]. A subsequent study on Australian football from 1992 to 1999 by Orchard et al. [37] confirmed these results. This study determined that high evaporation in the month before the game and low rainfall in the year before the game (dry conditions) were both significantly associated with the 63 noncontact ACL injuries observed during the study. The authors suggested that wet weather conditions resulted in lower ACL injury rates because these conditions decreased the COF of the shoe-surface interaction; they further recommended extra watering and covering the playing surface during periods of high evaporation in order to lower the rate of injury. Furthermore, a study of 156 semiprofessional rugby players over two seasons determined that greater rainfall in the prior year was associated with fewer injuries. Also, the number of injuries and the injury rate was higher during games played on hard ground (associated with dry conditions) [38].

Analyses of different surfaces during both wet and dry conditions have confirmed that the dry conditions create a higher COF of the shoe-surface interaction. Torg et al. [9] in 1974 compared the release coefficients during wet and dry conditions for two types of soccer cleats on grass and three older generation artificial turf surfaces. For both cleat models, the wet condition release coefficients were generally the same or lower when compared to the dry condition for all of the experimental surfaces. These results were confirmed by Heidt et al. [11] who tested five types of American football cleats on both wet and dry first-generation AstroTurf. This study determined that for all the cleat models, the peak rotational torque on dry AstroTurf was significantly greater that on wet AstroTurf (24.7 and 17.4 Nm, respectively). Altogether, these results suggest that the increased incidence of ACL injury observed during dry conditions is most likely a result of the increased COF of dry surfaces as compared to wet surfaces.

5.4.2 Temperature

The temperature of the shoe-surface interaction may affect the incidence of ACL injury; specifically, warm conditions are associated with higher rates of injury than cold conditions. In a study by Orchard et al. [5] of NFL football games from 1989 to 1998, the ACL injury rate was lower on cold days compared to hot days in outdoor stadiums but not in domes. The cause of this discrepancy is that the domes were insulated from the weather conditions, so temperature extremes did not change the ambient environment of the dome. The authors hypothesized that the lower incidence of injury in cold conditions was the result of reduced COF of the shoe-surface interaction.

Additionally, a comprehensive review by Orchard described an “early season bias” for knee injuries in a variety of sports (rugby, soccer, American and Australian football, etc.) whose competitive seasons begin in the fall and extend through the winter [3]. In these sports, an increased incidence of lower limb injuries was reported early in the season during the autumn (warmer) months; this bias was not seen in summer competitions of the same sports or in indoor sports. Orchard et al. [5] confirmed these results in NFL games from 1989 to 1998, as the incidence of ACL injury decreased in the colder months in outdoor stadiums but not in domes. The authors concluded that the early season bias for knee injuries was related to the weather, which altered the COF of the shoe-surface interaction; the early season games were played during warm, dry conditions that resulted in a high COF, while the late season games were played during cold, wet conditions that resulted in a low COF [3].

In the laboratory, it has been shown that the temperature of the shoe-surface interaction affects the release coefficient on AstroTurf; specifically, the release coefficient increases as the temperature increases [39]. Five shoe models (two turf cleats, basketball shoes, and soccer cleats) were tested for the rotational torsion release coefficient on dry AstroTurf at five temperatures: 52°, 60°, 78°, 92°, and 110°. As the temperature increased, there was a corresponding increase in the release coefficient for each shoe model tested. This study shows that higher temperature results in an increased COF of the shoe-surface interaction, suggesting that this is the cause of the greater incidence of ACL injury observed in hot conditions.

5.4.3 Male Focus

All of the major studies that have investigated how weather affects the COF and ACL injury have been conducted with male athletes. Again, this may be a result of the era during which the research was conducted; the previously described studies were all conducted before 2000 and involved either American or Australian football. However, both male and female athletes play sports in all weather conditions, and the gender of the athlete does not affect the water content of the surface or the temperature of the shoe-surface interaction. Therefore, the conclusions from these studies may be relevant for female athletes as well.

Critical Points

- Weather conditions (water content of surface, temperature of shoe-surface interaction) can affect incidence ACL injury.
- Dry conditions (low rainfall, high evaporation) result in increased incidence ACL injury and increased COF compared to wet conditions.
- Warm conditions (hot weather) result in increased incidence of ACL injury and increased COF when compared to cold conditions.
- Most weather research focused on male athletes but may be relevant for female athletes.

5.5 Biomechanical Adaptations

For all the studies described thus far in this chapter, a higher incidence of ACL injury was observed for shoe-surface interactions with higher COF. However, the reasons for the increased ACL injury rates have not been discussed. Previous research has suggested that when athletes encounter a high COF shoe-surface interaction, they alter their movement techniques in order to accommodate the change in the COF. The movement alterations lead to changes in the athlete's biomechanics that increase their risk for ACL injury. It is these biomechanical changes that may be the reason for the observed increase in ACL injury rates with high COF. In Sect. 5.2, specific kinematic and kinetic risk factors have been identified that increase the risk of ACL injury in female athletes. Two of the most critical risk factors are decreased knee flexion angle and increased knee loading (especially the combination of external valgus and internal rotation moments) during cutting movements, which replicate the ACL injury mechanism. According to the previous research, when the COF of the shoe-surface interaction is increased, athletes decrease their knee flexion angle and increase their knee loading during cutting tasks, thereby also increasing their risk for ACL injury.

5.5.1 Knee Flexion Angle

As described previously, female athletes that exhibit a decreased knee flexion angle during cutting movements are at greater risk for suffering an ACL injury. Previous research has also shown that healthy subjects will decrease their knee flexion angle during a cutting task when they experience a high COF shoe-surface interaction, thus increasing their risk of injury. In a study by Dowling et al. [35], healthy male and female athletes wearing running shoes performed a 30° sidestep cutting task on a low COF surface (0.38) and a high COF surface (0.87) at a constant speed. This study determined that, at foot contact, the athletes had a statistically significant decreased knee flexion angle on the high COF surface relative to the low COF surface (20.6° vs. 23.4°). The effect of this small change in knee flexion is unknown. Figure 5.9 illustrates the difference in the knee flexion angle of the athletes on the high and low COF surfaces. The authors concluded that the increased incidence of ACL injury observed with high COF shoe-surface interactions might be a result of biomechanical changes (like decreased knee flexion angle) that athletes adopt as a result of the high COF.

5.5.2 Knee Loading

Increased loading of the knee during cutting movements, particularly the combination of external valgus and internal rotation moments, has also been shown to increase the risk of ACL injury for female athletes. Prior research has indicated that healthy subjects will increase their knee loading during a cutting task when they experience a high COF shoe-surface interaction, thus increasing

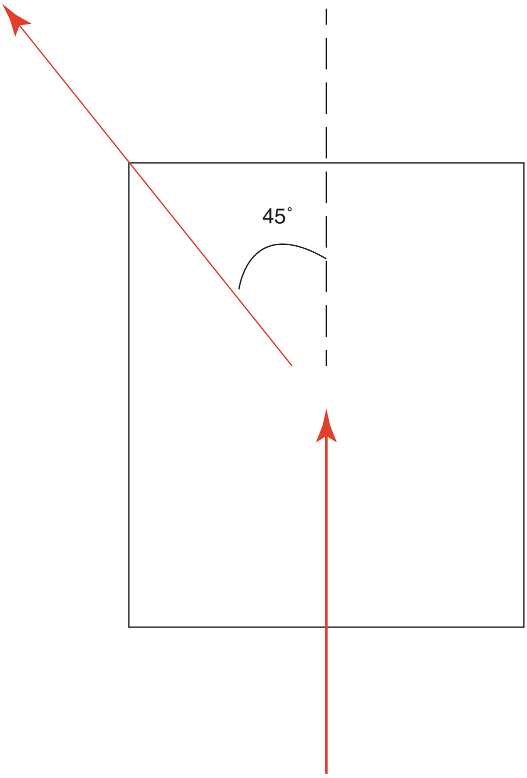

Fig. 5.11 Diagram of the 45° cutting movement performed on the sample track surface adhered to the force platform [40]. (Reprinted from Wannop et al. [40]; with permission of SAGE Publications, Inc.)

their risk of injury. Wannop et al. [40] conducted a study on knee loading in healthy athletes during the stance phase of a 45° cutting maneuver (Fig. 5.11). The athletes wore two different shoes during the cutting maneuver: a shoe with a smooth sole and a shoe with a tread sole that contained many rubber grooves and studs. The study first determined that the peak rotational torque was significantly higher for the tread shoe compared with the smooth shoe (23.89 Nm and 16.12 Nm, respectively). Then, a comparison was performed of the athletes' knee loading during the cutting task by shoe type. When wearing the tread shoe with a higher COF compared to the smooth shoe with a lower COF, the athletes exhibited significantly higher peak external knee valgus (224.0 Nm and 186.8 Nm, respectively) and internal rotation moments (36.23 Nm vs. 32.02 Nm, respectively) [40]. Furthermore, Dowling et al. [35] also determined that at foot contact during a cutting task, athletes had a significantly increased external knee valgus moment on the high COF surface relative to the low COF surface. Altogether, these studies suggest that the increased incidence of ACL injury observed with high COF shoe-surface interactions might be a result of increased loading at the knee, especially an increased external valgus moment, which athletes adopt as a result of the high COF.

One study [41] did determine that varying the cleat model during running and cutting tasks did not affect athletes' knee loading. Fifteen male professional soccer players completed three running tasks on third-generation FieldTurf (straight-ahead run, sidestep cutting at 30°, and sidestep cutting at 60°) while wearing either bladed soccer cleats or studded soccer cleats. The authors determined that varying the cleat models did not result in significant differences in knee loading during any of the running tasks. However, the COF of the shoe-surface interaction was not determined for each cleat model, and it is possible that the cleat models had similar COF with the FieldTurf. Since the previous studies have suggested that knee loading is related to COF, if the COF of the shoe-surface interaction did not change, then it stands to reason that the knee loading also would not change.

5.5.3 Lack of Research

Unfortunately, few studies have focused on how female athletes alter their biomechanics as a result of changes in the shoe-surface interaction. For example, there have been no investigations into variations in muscle activation as a result of changing the shoe-surface interaction. The few studies that examined kinematic and kinetic changes as a result of changes in the shoe-surface interaction were relatively small studies (fewer than 25 subjects) that did not specifically focus on female athletes. Therefore, more research is necessary to determine how changing the shoe-surface interaction alters female athletes' biomechanics during activities that replicate the ACL injury mechanism.

Critical Points

- Athletes adopt biomechanical changes as a result of high COF, increase risk for ACL injury.
- High COF shoe-surface interaction causes decreased knee flexion angle during cutting maneuvers (risk factor for ACL injury).
- High COF shoe-surface interaction causes increased knee loading, especially external knee valgus moment, during cutting maneuvers (risk factor for ACL injury).
- Few studies have examined biomechanical changes in female athletes, more research required.

5.6 Conclusions and Future Directions

Altogether, research has shown that increasing the COF of the shoe-surface interaction through changes in the shoe design, playing surface, or weather leads to an increase in the incidence of ACL injury (Tables 5.2 and 5.3), especially for female athletes. This increase in injury rates is most likely a result of the athletes' biomechanical adaptations to the high COF, such as decreased knee flexion angle and increased knee loading that place them at greater risk for injury. As such, future research should focus on investigating methods to alter both the shoe-surface interaction and the athletes' biomechanical adaptations in order to decrease the incidence of ACL injury.

While it is well established that higher COF of the shoe-surface interaction increases the risk for ACL injury, there is no consensus as to what constitutes too high COF. There has been little research to determine the threshold for COF that optimizes athletic performance while minimizing the risk for ACL injury. Knowing this optimal threshold for COF could significantly decrease the incidence of ACL injury since future cleats and surfaces could be designed to not exceed this value. In terms of defining this optimal threshold, one study experimentally suggested that a COF of 0.5 was adequate to complete a cutting maneuver, as COF values over 0.5 did not lead to better performance by the athletes [42]. Furthermore, Ekstrand and Nigg [43] have suggested that the guiding principle behind cleated shoe design should be to constrain the COF of the shoe-surface interaction to an optimal range, where the rotational torque is minimized to avoid injury but the translational COF is maximized to allow for peak performance during sporting maneuvers. However, more research is necessary to accurately determine the optimal threshold for a variety of cleated shoe designs and surfaces.

Once an optimal threshold for COF has been determined, regulations should be enacted that limit both the cleated shoe designs and the playing surfaces from exceeding this threshold. In terms of cleated shoe designs, there are already fairly strict regulations for many sports to ensure player safety. In collegiate American football, the cleats must be ≥3/8″ wide and <1/2″ long in order to protect the players from excessive rotational torque [9]. As such, additional regulations for cleats may not greatly benefit the athletes. However, the COF of the playing surface is not regulated to the same extent. Additionally, the COF of the playing surface can be easily controlled because these surfaces are installed and maintained by professional organizations that must report to governing bodies, such as the NCAA or the state and federal governments. Therefore, more research should be conducted in order to advise these governing bodies as to how to restrict the maximum COF of the playing surface, which will help to reduce the risk of ACL injury among all athletes.

While weather is a significant factor that affects the shoe-surface interaction, it is also the most uncontrollable factor. Preemptively watering the playing surface to increase the water content has been suggested as an effective method to reduce injuries [3], but this results in a high environmental cost. Furthermore, restricting play to the colder months of the year would negatively impact the athletes' ability to participate in the sport. As such, it would be more beneficial to focus future work on the factors affecting the shoe-surface interface that can be easily controlled and regulated.

Table 5.2 Studies assessing environmental factors on the incidence of ACL injuries in female athletes

Study	Population	Exposures	Playing surface	ACL injury rate (per 1000 exposures)
Pasanen et al. [6]	Top-level Finnish female floorball 1 season	Artificial 601 Wooden 971	Wooden Artificial rubberized floor	Wooden 2.1 Artificial 5.0
Fuller et al. [29]	Collegiate soccer NCAA Injury Surveillance System, 2005–2006 Match injuries	Turf 7195 men 6997 women Grass 27,803 men 37,258 women	Synthetic infill artificial turf Grass	Turf 0.42: men 1.29: women ($P = 0.09$) Grass 0.47: men 1.64: women ($P < 0.01$)
Fuller et al. [30]	Collegiate soccer NCAA Injury Surveillance System, 2005–2006 Training injuries	Turf 56,504 men 46,998 women Grass 208,842 men 233,498 women	Synthetic infill artificial turf Grass	Turf 0.02: men 0.02: women Grass 0.03: men 0.09: women
Steffan et al. [28]	Norwegian female soccer Aged ≤16 years 2005 season	Grass 73,044 Turf 39.979 Gravel 25,156 Indoor 4542	Grass third-generation artificial turf Gravel Indoor floor	Overall 0.08 3 on grass, 4 on turf, 2 on gravel, 2 indoor floor. Only 6 noncontact ACL injuries, limited statistical power
Olsen et al. [2]	Norwegian team handball Aged 17–33 years 1989–2000	37,114 men 57,022 women	Wooden Artificial rubberized floor	Wooden 0.41: women 0.32: men Artificial 0.96: women ($P = 0.03$ compared to wooden) 0.20: men ($P = 0.001$ compared to women)

NCAA National Collegiate Athletic Association (USA)

In terms of the biomechanical adaptations, training programs could be used to teach the athletes how to safely alter their movement when they encounter a high COF shoe-surface interaction. Injury prevention programs, such as those discussed in Sect. 5.3, could include training with different COF shoe-surface interactions in order to safely introduce high COF to the athletes and to teach compensation methods that do not increase the risk for injury. This type of training could be easily integrated into existing programs by using different artificial surfaces that the athletes might encounter in their sport or by varying the cleats that the athletes wear. Altogether, incorporating training for high COF shoe-surface interactions into the standard prevention programs may help to further decrease the incidence of ACL injury.

Regulations on shoe cleat design and artificial surfaces can also be used to lower the overall COF of the shoe-surface interaction. Because there is a perceived trade-off between athletic performance and injury protection, regulations affecting all athletes in a given sport are necessary in order to ensure that the athletes are both competitive and protected from injury. Already, organizations such as the NFL and youth soccer leagues in many states in the United States have some regulations in place regarding the length, number, and material composition of cleats, as well as standards for artificial turf. However, other major sporting organizations such as the NCAA and the Federation Internationale de Football Association (FIFA) do not closely regulate either athletes' footwear or the COF of the playing surfaces. Based on research discussed in

Table 5.3 Studies assessing environmental factors on the incidence of ACL injuries in male athletes

Study	Population	Exposures	Playing surface, environmental factors	ACL injury rate
Powell and Schootman [7]	American pro football 1980–1989	Not given	Natural grasses AstroTurf	No difference overall incidence ACL injuries Special teams only Grass: 12/48 AstroTurf: 12/48
Lambson et al. [1]	American football High school 1989–1991	Not given	Natural grass	Edge cleat shoe: 0.017% (38/2231 players) Non-edge cleat shoes: 0.005% (4/888 players) ($P = 0.0066$)
Ekstrand et al. [27]	492 elite European soccer Aged 16–39 years 2003–2004	116,744	Natural grasses third-generation artificial turf	"Knee sprains"—no difference in incidence between grass and turf Did not provide data for ACL injuries
Orchard et al. [4]	Australian football 1992–2004	Not given	Variety of natural grasses Ground hardness, rainfall, evaporation	88 noncontact ACL injuries. Significant risk factors: grass type (Bermuda), 1st grade match, earlier stage of season
Meyers and Barnhill [25]	American football High school 1998–2002	Not given	Natural grasses Synthetic artificial turf temperature, humidity, rainfall	ACL injury incidence rates per game 1.0 grass, 0.4 turf
Orchard and Powell [5]	American pro football NFL Injury Surveillance System, 1989–1998	Not given	Natural grasses Artificial turf Dome Temperature, rainfall	ACL injury incidence rates per team season Playing surface: 0.8 grass, 0.9 turf, 0.9 dome Rainfall: 0.7 dry, 1.0 wet Temperature: 0.9 hot, 0.6 cold
Orchard et al. [37]	Australian male football Aged 23 ± 3.8 years 1992–1999	100,820	Evaporation, rainfall, grade of match, age, weight, height, body mass index, history prior ACL tear	0.62 noncontact per 1000 exposures Significant risk factors: history prior ACL injury, low rainfall, 1st grade match, increased height

NFL National Football League (USA)

this chapter, regulations regarding the minimum number of cleats, cleat placement, and cleat size should be developed for all major sports organizations in order to reduce the risk for ACL injury and should be enforced for both professional and recreational athletes. Furthermore, researchers and sporting organizations should work together to develop a maximum allowable COF for artificial surfaces. By limiting the COF of the playing surface, all athletes would be equally protected against excessive COF and would theoretically reduce their risk for injury. However, further research is required to determine the ideal COF threshold that optimizes performance while minimizing risk for ACL injury.

Based on previous research, female athletes can reduce their risk for ACL injury due to the shoe-surface interaction by following a few precautions. First, female athletes should select their athletic footwear carefully; they should avoid standard American football cleats and edge cleats and instead should wear traditional soccer cleats or turf cleats. They should also attempt to match their chosen footwear to the playing surface, e.g., wearing soccer cleats for grass surfaces and turf cleats for artificial surfaces, especially first- and second-generation artificial turf. Also, they should avoid artificial rubberized surfaces or wear shoes with smooth soles when it is necessary to compete on these surfaces. While weather is less controllable, female athletes in warm, dry climates should take extra care to match their footwear to the weather conditions and the playing surfaces. Finally, they should participate in training programs that will teach them how to compensate for a high COF shoe-surface interaction without putting themselves at risk for ACL injury. All of these recommendations can help female athletes to decrease their risk for ACL injury due to a high COF shoe-surface interaction.

Critical Points

- Further research is required to determine threshold for maximum COF that optimizes athletic performance while minimizing risk for ACL injury.
- Once threshold is identified, regulations should limit shoe designs and playing surfaces from exceeding this threshold.
- Injury prevention training programs should include training for high COF shoe-surface interactions.
- Footwear selection, matching the footwear to the playing surfaces and weather conditions, and training can help females to decrease their risk for ACL injury due to a high COF shoe-surface interaction.

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6

Gender Differences in Muscular Protection of the Knee

Benjamin Noonan and Edward M. Wojtys

Abstract

This chapter summarizes gender differences in various biomechanical properties of the knee including laxity, anteroposterior translation, active stiffness, and quadriceps and hamstrings strength. In addition, gender differences in proprioception, balance, muscle reaction time, muscle recruitment patterns, and time to reach peak torque are discussed.

6.1 Introduction

Several different features provide protection to the knee joint and anterior cruciate ligament (ACL) during physical activity, including the knee's structure and the neuromuscular system. This system generates and limits the inherent qualities of the knee including laxity, stiffness, and strength. Parameters of this system that can be measured include proprioception, muscle reaction time, and muscle time to peak torque.

As one of the inherent qualities of the knee, laxity has been defined as "indicating slackness or lack of tension in a ligament" [1], with excessive laxity being represented by abnormal displacements of the tibia in relation to the femur. Stiffness is the resistance to displacement of either a joint or a muscle exhibited across a range of applied forces (N/mm) that produce the displacement. Stiffness also describes a combined restraint system which includes both passive structural properties of the musculotendinous unit and active resistance produced by actin-myosin coupling. Strength can be evaluated in several ways including concentric, isometric, and eccentric modes; as well as isotonic and isokinetic contractions.

Distinct from the inherent qualities of the knee, the neuromuscular protection system relies on three components: sensory or afferent input from the surroundings, peripheral and central processing of these inputs, and efferent muscular response. The afferent or sensory portion of the motor protective system is often assessed by measuring motion at the knee or core, as well as balance. Input processing is frequently determined by muscular reaction times and muscular responses according to the time to generate peak torque during voluntary muscular contractions of the knee.

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6.2 Qualities of the Knee

6.2.1 Laxity

Laxity has been defined as "indicating slackness or lack of tension in a ligament" [1], with excessive laxity being represented by abnormal displacements of the tibia in relation to the femur. The passive soft tissue restraints which prevent abnormal displacement are capsular, ligamentous, and muscular. Basic science anatomy studies have shown that females exhibit greater internal rotation laxity from 0 to 50° of flexion [2], and although ligamentous laxity is often proposed as a risk factor for knee injury, the evidence is mixed [3–6]. In a study of United States Military Academy cadets, women had greater knee arthrometer (KT-2000) anterior tibial translation and more generalized joint laxity (small finger metacarpophalangeal hyperextension, elbow, and knee hyperextension and ability to touch thumb to forearm bilaterally) than men [6]. In this cohort, generalized laxity and KT-2000 anterior tibial translation were significantly greater in individuals who sustained a noncontact ACL injury compared with uninjured subjects. KT-2000 values greater than one standard deviation above the mean increased the relative risk of noncontact ACL injury by 2.7 in women. A 1.3-mm increase in anterior tibial translation was associated with a fourfold increase in ACL injury risk. In another study, 47% of the knees with this degree of increased anteroposterior (AP) translation eventually suffered an ACL injury [5]. Increased anterior-posterior knee joint laxity has also been shown to be one of several risk factors for subsequent ACL injury in a cohort of healthy male and female collegiate athletes [7]. These prospective findings were corroborated by a case-sectional study demonstrating that the healthy contralateral knees of noncontact ACL injured patients had greater anterior and interior rotational laxity when compared to the healthy knees of control patients [4]. Further, high-grade pre-reconstructive knee joint laxity in patients undergoing primary, isolated ACL reconstruction surgery may be associated with a higher incidence of a required revision ACL surgery [3]. Given the relationship of laxity and ACL injury risk, others have sought to determine if laxity is modifiable or affected by other variables such as fatigue or hormonal influences.

Fatigue is commonly experienced during athletic events which have led some to investigate its effects on laxity. Studies conducted on collegiate soccer and basketball players found that females had significantly greater AP translation at rest compared with males (6.05 and 4.80 mm; respectively, $P = 0.021$), which did not change significantly after a fatiguing protocol [8, 9]. In another study, a quadriceps and hamstring fatiguing protocol consisting of repetitions of isokinetic knee flexion and extension performed until a 50% decrease in work occurred resulted in an increase in AP translation without significant differences between men and women [10].

Another variable which may affect laxity is hormonal fluctuations that occur over the course of a menstrual cycle [11–15]. The effects of hormonal levels on laxity are variable; a systematic review reported mixed results with six of nine studies reporting no differences [15]. Newer evidence points to increased AP laxity [11], genu recurvatum, and generalized joint laxity [13] across the menstrual cycle, but the combined body of evidence is still of lower quality and needs to be further validated [16].

Critical Points

- Increased knee laxity may increase the risk of ACL injury.
- In general, female athletes have greater AP translation than male athletes.
- The impact of hormones and the menstrual cycle on knee laxity are not clear; newer data show increased translation across the menstrual cycle.
- The impact of fatigue on AP tibial translation is mixed.

6.2.2 Stiffness

Stiffness can be both a blessing and a curse. Postoperative stiffness which decreases range of knee motion represents a major complication, while protective stiffness across the knee joint is a necessary component of injury prevention. Stiffness in the joint injury prevention vernacular is the resistance to displacement of either a joint or a muscle across a range of applied forces (N/mm). Stiffness has both a passive inherent structural component determined by the musculotendinous unit and an active resistance capacity determined by the actin-myosin binding of the muscle. While both components are susceptible to fatigue, the active component is also dependent on the muscle recruitment time [10, 17]. Stiffness across a joint is determined by the status of the capsule, ligaments, muscle, and tendons crossing the joint. The tensile stiffness of a muscle is dependent upon several factors: (1) muscle activation, (2) cross-sectional area and pennation angle of the muscle fibers, (3) the amount and arrangement of passive connective tissue in the muscle, (4) the change in length of the muscle fiber, (5) the velocity of the change in length, and (6) tendon stiffness [18]. The ability to increase muscle stiffness across a joint can reduce damaging loads that have the potential to injure ligaments and other passive structures [18–22]. In general, males produce greater active stiffness than females [18, 20–22].

Men are able to actively increase their muscle stiffness in response to an anterior tibial translation threefold compared with a twofold increase generated by women (Table 6.1) [18]. Studies have also shown that males maintain greater muscle stiffness during various loading conditions (0 kg, 6 kg, and 20% of maximal voluntary contraction) in both knee extension and flexion compared with females [19, 21].

Several of these aforementioned studies have been conducted in laboratory settings to measure knee joint stiffness, while others have used a more functional protocol [20, 23]. For instance, Granata et al. [20] reported that in two-legged hopping tasks (2.5 Hz, 3.0 Hz, or at a preferred hopping rate), male subjects maintained greater stiffness at all frequencies compared with females (Table 6.1). Further, Wang et al. [23] demonstrated that females have lower relaxed and contracted vastus lateralis muscles stiffness and lower knee joint musculoarticular stiffness during knee extension than males (Table 6.1).

Stiffness may be measured in both the AP translation or in axial rotation. The dynamic rotational stiffness of 24 Division I collegiate athletes participating in either low (bicycling, crew, and running)- or high (basketball, volleyball, and soccer)-risk ACL injury pivoting sports was assessed by applying rotational torques to the lower extremities and measuring the resultant internal tibial rotation at knee angles of 30° and 60° [22]. Females exhibited greater active resistance to internal tibial rotation in both knee flexion angles compared to males (30°, 4.4 and 7.4 mm, respectively; 60°, 3.4 and 5.5 mm, respectively). Especially concerning was the finding that the females in high-risk sports generated only a 159% increase in rotational stiffness, whereas the males in high-risk sports and females in low-risk sports were able to increase stiffness by 275% and 191%, respectively (Table 6.1). It is unclear whether training of high-risk female athletes was unsuccessful or if the maximal rotational joint stiffness for women was significantly lower due to limits in their muscle capacity [22]. The decreased axial rotational stiffness in females is of concern because it has been shown that internal tibial rotation is a potent stressor of the ACL [24].

Critical Points

- Males have significantly greater ability to generate active stiffness in both sagittal and axial planes compared to females.
- Axial plane stiffness is critical in ACL protection because internal tibial torque greatly increases ACL strain.

6.2.3 Strength

Muscle force powers movement of both the femur and tibia and also absorbs impact. The quadriceps muscle is a potent shock absorber for the knee [25]. The knee extensors have three distinct energy absorption phases during gait: (1) an initial shock absorbing pattern with energy being absorbed by the knee during weight acceptance, (2) a major absorption pattern during late push-off that lasts until maximal knee flexion, and (3) a deceleration of the swinging leg prior to heel

Table 6.1 Gender differences in muscular stiffness

Study	Subject data	Testing protocol, ° knee flexion	Results			
			Male	Female	Difference (%)	Difference significant?
Blackburn et al. [19]	18–28 yo recreational athletes	30° flexion	Nm/rad: 223.7 ± 40.2	160.7 ± 23.2	48	Yes
Granata et al. [20]	21–33 yo recreational athletes	Hopping rate: 2.5 Hz 3.0 Hz Preferred	kN/m: 31 ± 8 43 ± 8 26 ± 9	24 ± 5 35 ± 7 19 ± 8	29 23 37	Yes Yes Yes
Granata et al. [21]	21–33 yo recreational athletes	Quadriceps 0 kg perturbation	Nm/rad: 97.6 ± 31.1	72.2 ± 30.3	35	Yes
		Quadriceps 6 kg perturbation	262.2 ± 78.3	170.1 ± 29.0	54	Yes
		Quadriceps 20% MVE perturbation	326.9 ± 105.9	182.5 ± 43.2	79	Yes
		Hamstrings 0 kg perturbation	73.3 ± 25.1	53.6 ± 16.2	37	Yes
		Hamstrings 6 kg perturbation	196.8 ± 36.9	130.5 ± 22.2	51	Yes
		Hamstrings 20% MVE perturbation	159.1 ± 51.0	94.0 ± 22.0	69	Yes
Wojtys et al. [18]	19–31 yo sedentary to elite athletes	Sagittal shear stiffness	N/mm: 70.9	40.7	74	Yes
Wojtys et al. [22]	College athletes, low and high-risk sports		% increase in stiffness from passive to active state:			
		Tibial rotation, 30° flexion, low risk	218 ± 22	178 ± 9	22	Yes
		Tibial rotation, 60° flexion, low risk	231 ± 21	185 ± 12	25	Yes
		Tibial rotation 30° flexion, high risk	275 ± 39	159 ± 13	73	Yes
		Tibial rotation 60° flexion, high risk	258 ± 40	171 ± 18	51	Yes
Wang et al. [23]	18–35 yo recreational athletes	Probe/accelerometer with passive perturbation of Vastus Lateralis	N/m Relaxed: 364.4 ± 52.0	270.3 ± 33.3	26	Yes
		Both relaxed and contracted state	Contracted: 495.1 ± 71.0	332.3 ± 85.4	33	Yes

Data shown are mean ± standard deviation
MVE maximal voluntary exertions
Difference (%): % differences between groups in adjacent columns
Units for each result are reported in the first data point in male column and are representative of entire study cited
Difference significant? $P \leq 0.05$ between groups in adjacent columns

contact [25]. There are several modes of muscle function during which strength can be measured based on length of muscle (isometric, concentric, and eccentric) and speeds of shortening or lengthening which can affect the forces generated [26]. The eccentric mode generates the highest forces and is most applicable to function.

Poor muscle strength to body weight ratio may be a risk factor for lower extremity injury [6], but the evidence is not unanimous [27]. Some evidence suggests that knee flexors have the potential to reduce stress on the ACL. The knee extensors function more as an antagonist [28] but do contribute significantly to increased stiffness across the knee joint. The hamstrings-to-quadriceps (H:Q) ratio has been shown to correlate with ACL injury risk [29–34]. Strength deficits have also been shown to be associated with ACL reconstruction failure and reduced rate of return to sport following ACL reconstruction [35, 36].

Not surprisingly, athletes demonstrate greater absolute quadriceps and hamstring strength compared with gender-matched nonathletic controls [31]. Male athletes consistently display increased normalized quadriceps strength (29–38%) compared with female athletes, while mixed results are reported for hamstring strength (Table 6.2) [18, 37, 38]. Higher H:Q ratios have been measured in some male high school athletes [29, 33], while other studies [31, 34] failed to replicate these results (Table 6.3).

Peak knee extensor and flexor torque increase with maturation in both sexes [39]. In females, knee extensor torque increases more rapidly (torque 20% greater in 13-year-old subjects than 9-year-old subjects) than knee flexor torque (no increase after age 11), leading to muscular imbalances and possible increases in ACL strain. Absolute strength is similar in 7–11-year-old male and female athletes [40]. When comparing H:Q ratios, immature (10–13-year-old) female soccer players demonstrate reduced ratios compared with males and mature (14–18-year-old) females in some but not all studies [32, 39, 40]. Further, younger females may exhibit greater bilateral differences in H:Q ratios between dominant and nondominant legs than males, though these side-to-side differences may disappear with full maturation [41].

Proximal hip strength is an important factor in overall knee injury protection since these muscles may provide distal knee stability in the frontal plane, and poor hip strength may prospectively predict ACL injuries [42]. It has been demonstrated that baseline hip external rotation and abduction strength relative to body mass were significantly lower in male and female athletes that subsequently suffered and ACL injury compared with non-injured athletes (external rotation, 17.2 ± 2.9 and 22.1 ± 5.8% body mass, respectively; $P = 0.003$ and abduction, 30.8 ± 8.4 vs. 37.8 ± 7.6% body mass, respectively; $P < 0.001$). This study further indicated that athletes who demonstrated low risk hip external rotation and abduction strength relative to their established clinical cutoffs (strength ≤20.3% or 35.4% body mass, respectively) had an ACL injury risk that decreased from 3% to 1%, while athletes who demonstrated high risk strength had an ACL injury risk that increased from 3% to 7%. More research is needed to elucidate proximal strength contributions to distal knee stability.

Pertinent to this discussion of knee injury research is the velocity of sporting movements compared to laboratory research. The angular velocity of the knee joint during high-intensity sports activities such as a soccer kick is much faster (745–860°/s) than isokinetic testing at 300°/s [43], raising questions about the value of isokinetic testing in the rehabilitation environment. Males are able to increase their H:Q ratio from 47% to 81% as contraction speed increases from 30°/s to 360°/s (Fig. 6.1), whereas females are not able to do so [44]. This finding is consistent with other maturation-specific gender differences in neuromuscular control, but no definitive mechanism has been proposed [45]. Reduced H:Q ratios have also been reported during the first 50 ms of knee contractions in both male and female soccer players [46]. Reduced H:Q ratios are concerning because they are associated with ACL injury [29, 31, 34].

Similar to laxity, strength is affected by prior exercise. H:Q ratios are affected by fatigue, as both male and female soccer players have demonstrated a decrease of 8–29% after fatiguing protocols [47–49]. Protocols that induce fatigue include sprints [47, 49] and isokinetic knee extension and flexion [48]. Unfortunately, there have been no direct comparisons in the sex differences response to fatigue.

Critical Points

- Male and female H:Q ratios are age dependent showing mixed results; some studies reporting greater ratios in male versus female athletes.

Table 6.2 Gender differences in knee extensor, flexor peak torque

Study	Subject data	Testing protocol	Results			
			Male	Female	Difference (%)	Difference significant?
Bowerman et al. [31]	18–25 yo college athletes	Extensors 60°/s	Nm: 253.14 ± 65.0	167.6 ± 28.8	51	Yes
		Flexors 60°/s	131.81 ± 39.7	86.9 ± 14.1	52	Yes
Wojtys et al. [18]	19–31 yo sedentary to elite athletes	Extensors 60°/s	ft lb/lb body weight: 89 ± 10	69 ± 14	29	Yes
		Flexors 60°/s	45 ± 7	37 ± 8	22	No
Lephart et al. [37]	College athletes	Extensors 60°/s	Nm: 271.68 ± 59.3	222.93 ± 30.9	22	Yes
		Flexors 60°/s	131.72 ± 21.9	113.74 ± 23.6	16	Yes
Pincivero et al. [38]	20–28 yo recreational athletes	Extensors 180°/s	Nm/kg: 2.11 ± 0.22	1.53 ± 0.21	38	Yes
		Flexors 180°/s	1.23 ± 0.15	0.93 ± 0.14	32	Yes
Holm and Vollestad [40]	7–12 yo athletes	7 yo, flexors/extensors 60°/s	Nm: 22 ± 7/37 ± 8	21 ± 7/39 ± 11	5/5	No/no
		8 yo, flexors/extensors 60°/s	28 ± 6/47 ± 9	25 ± 7/45 ± 12	12/4	No/no
		9 yo, flexors/extensors 60°/s	35 ± 9/58 ± 12	32 ± 6/60 ± 14	9/3	No/no
		10 yo, flexors/extensors 60°/s	39 ± 8/66 ± 5	37 ± 9/71 ± 14	5/7	No/no
		11 yo, flexors/extensors 60°/s	48 ± 10/85 ± 19	48 ± 10/80 ± 14	0/6	No/no
		12 yo, flexors/extensors 60°/s	56 ± 11/97 ± 18	52 ± 13/99 ± 25	8/2	Yes/no

Data shown are mean ± standard deviation
Difference (%): % differences between groups in adjacent columns
Units for each result are reported in the first data point in male column and are representative of entire study cited
Difference significant? $P = 0.05$ between groups in adjacent columns

Table 6.3 Gender differences in hamstrings-to-quadriceps ratio

Study	Subject data	Testing protocol	Results ratio %			
			Male	Female	Difference (%)	Difference significant?
Bowerman et al. [31]	18–25 yo college athletes	Flexion/extension, 60°/s	52.0 ± 8.5	52.4 ± 7.3	0	No
Rosene et al. [34]	College athletes	Flexion/extension, 60°/s	50.9 ± 11.2	50.1 ± 7.7	0	No
		Flexion/extension, 120°/s	54.5 ± 12.1	56.4 ± 20.8	3	No
		Flexion/extension, 180°/s	59.7 ± 13.9	59.4 ± 10.9	0	No
Barber-Westin et al. [30]	9–10 yo athletes	Dominant leg, 180°/s	81 ± 15	77 ± 22	5	No
		Nondominant leg, 180°/s	75 ± 19	73 ± 10	3	No
Buchanan and Vardaxis [32]	11–13 yo athletes	Flexion/extension, 60°/s	47 ± 3	41 ± 4	15	No
	15–17 yo athletes	Flexion/extension, 60°/s	43 ± 3	51 ± 4	16	No
Anderson et al. [29]	High school athletes	Flexion/extension, 60°/s	61.8	56.8	9	Yes
		Flexion/extension, 240°/s	62.9	73.5	17	Yes
Hewett et al. [33]	High school athletes	Dominant leg, 60°/s	62 ± 8	55 ± 9	13	Yes
		Nondominant leg, 60°/s	67 ± 7	47 ± 8	43	Yes
Holm and Vollestad [40]	7–12 yo athletes	7 yo, 60°s/240°s	60 ± 14/55 ± 17	54 ± 13/58 ± 19	11/5	No/no
		8 yo, 60°s/240°s	61 ± 13/65 ± 14	57 ± 12/54 ± 12	7/20	No/yes
		9 yo, 60°s/240°s	61 ± 12/62 ± 11	55 ± 11/57 ± 12	11/9	Yes/no
		10 yo, 60°s/240°s	61 ± 12/57 ± 14	53 ± 09/55 ± 12	15/4	Yes/no
		11 yo, 60°s/240°s	68 ± 11/61 ± 14	51 ± 09/59 ± 18	33/3	Yes/no
		12 y, 60°s/240°s	58 ± 08/64 ± 12	53 ± 10/55 ± 13	9/16	Yes/yes

Data shown are mean ± standard deviation
Difference (%): % differences between groups in adjacent columns
Units for each result are reported in the first data point in male column and are representative of entire study cited
Difference significant? $P = 0.05$ between groups in adjacent columns

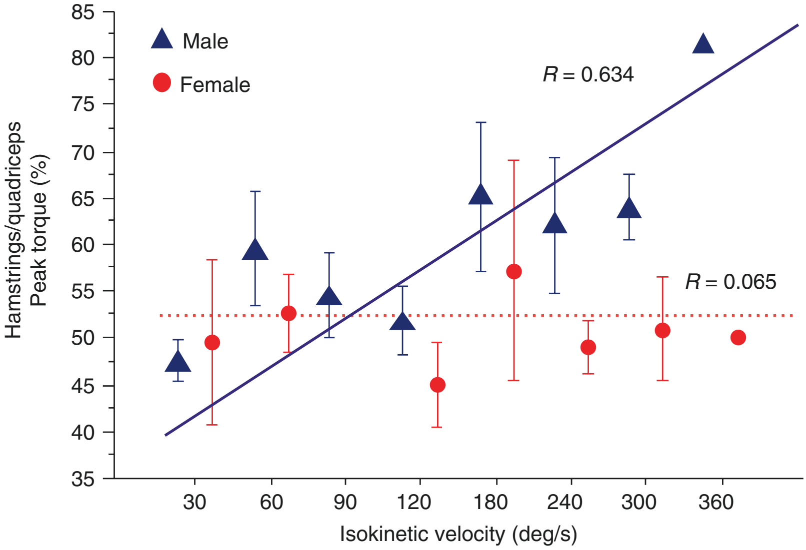

Fig. 6.1 Hamstrings-to-quadriceps ratio in female and male subjects diverges with increasing angular velocity [44] (Reprinted from Hewett TE, Myer GD, Zazulak BT (2008) Hamstrings to quadriceps peak torque ratios diverge between sexes with increasing isokinetic angular velocity. J Sci Med Sport 11 (5):452–459; with permission from Journal of Science and Medicine in Sport, Elsevier Publishers)

- Hamstring strength lags behind quadriceps strength through maturation, negatively impacting the H:Q ratio in young adults.
- Sex differences in H:Q ratios are amplified with increasing angular velocities.
- H:Q ratios decrease with fatigue in both males and females.
- Persistent strength deficits are associated with ACL reinjury as well as a lower rate of return to sport.
- Hip strength has been shown to be associated with ACL injury.

6.3 Neuromuscular System

6.3.1 Proprioception

Proprioception is the sense of joint and body position in space. Although the role of proprioception is central to athletic performance and protection from injury, it is not well understood. When this system is not optimized, increased ligament strain, articular cartilage shear, and/or bone impact may occur.

In one study, female athletes displayed statistically significant, but clinically minimal, delays in the threshold to detect passive motion (TTDPM) when the knee was moved into extension compared with males (2.95° and 2.11°, respectively, $P = 0.04$) [9]. There were no significant gender differences in TTDPM when the knee was moved into flexion. After a fatiguing protocol, a statistically significant increase was noted in TTDPM as the knee moved into extension in females (from 2.95° to 4.48°, $P \leq 0.05$) but not in males (from 2.11° to 2.82°); the clinical significance of which is questionable [8].

A more integrated measure of proprioception may be accomplished through balance testing, which is variable across different sports and levels of competition [50]. Balance performance appears to be trainable and may lead to improvement in athletic performance [51]. In one study, female soccer athletes displayed significantly better balance than male athletes on a commercial balance platform [9]. A fatiguing protocol of maximal effort isokinetic knee flexion and extensions did not affect balance for either males or females [8]. An athlete needs to be able to control the position of their extremities and trunk in order to achieve good balance control, which has led to investigations into limb and trunk proprioception and positioning with ACL injury risk.

Ground reaction forces and knee angles during landing from a jump have been correlated with ACL injury risk, leading to investigations regarding trunk and knee angles during jump landing [52] which is an area of incomplete research [53]. During landing from a 60-cm drop jump, male and female subjects demonstrated greater peak knee (22°) and hip (31°) flexion angles when asked to land with substantially greater (47°) trunk flexion [52]. It should be noted that landing with this degree of trunk flexion would likely be prohibitive during athletic activities as it would likely lead to decrements in sport-specific performance.

Critical Points

- Female athletes have better single leg balance than do male athletes.
- The contribution of trunk mechanics to ACL injury risk is still unclear.

6.3.2 Muscle Reaction Time

Central processing of peripheral inputs and motor responses is often evaluated using muscle reaction time. Women display shorter reaction times and tend to activate their quadriceps faster than male subjects after a sudden forward and either external (90.8 vs. 100.0 ms) or internal (89.8 vs. 96.8 ms) rotation torque to the trunk with a fixed tibia [54]. In one study, 16 female high school volleyball players performed a drop jump from increasing heights (15, 30, and 45 cm) [55]. As the drop height increased, muscle activation of the quadriceps during the preparatory phase of landing increased without a concomitant increase in hamstring activity, resulting in decreased H:Q ratios (1.9, 1.6, and 0.9, respectively). Quadriceps-dominant recruitment patterns are concerning in that powerful or unopposed contractions of the quadriceps have the potential to increase strain on the ACL [28]. However, the quadriceps can increase knee stiffness and may be capable of protecting the ACL when the transknee forces are balanced in the optimal knee position.

Critical Points

- Females recruit the quadriceps faster than males after perturbations to the knee and in preparation for landing from a jump which can increase ACL strain.

6.3.3 Time to Peak Torque

Several authors (Table 6.4) have reported no significant differences in time to peak torque between male and female subjects [9, 30, 31]. Huston and Wojtys reported that the force output of elite athletes and nonathletic males and females tested isokinetically at either 60°/s or 240°/s showed no significant differences in time to peak torque in knee extension between athletes and nonathletes [56]. At both speeds, female athletes exhibited slower knee flexion time to peak torque than all males and female nonathletes. Male athletes displayed significantly faster time to peak torque values than did male nonathletes. In another study, males showed a delay in hamstring activity during a jump landing while quickly decelerating and catching a netball pass at chest level compared to females [57]. Electromyographic outputs recorded for the quadriceps, hamstrings, and gastrocnemius showed that all muscle groups demonstrated prestop electrical activity, suggesting a preprogramed activity which may be an important anticipatory protection mechanism. The only sex differences recorded were a delay in the recruitment of the semimembranosus muscle in male subjects. Interestingly, the delayed onset of the hamstrings in the male athletes coincided with the timing of peak anterior force on the knee joint. The premature firing in the female group which preceded peak joint stress may not be more protective [57].

One investigation evaluated gender and maturation differences in time to peak torque for internal and external tibial rotation. A total of 94 athletes were separated into two age groups: 11–13 years old and 14–17 years old [58]. The older male athletes had significantly faster times in achieving hamstring peak torque than age-matched females (Table 6.4).

Critical Points

- Most studies have reported no significant differences in time to peak torque between sexes and across maturation levels.

Table 6.4 Gender differences in time to peak torque

Study	Subject data	Testing protocol	Results (ms)			
			Male	Female	Difference (%)	Difference significant?
Huston and Wojtys [56]	Division I college athletes	Extensors, 60°/s	408	420	3	No
		Flexors, 60°/s	328	430	24	Yes
		Extensors, 240°/s	153	158	3	No
		Flexors, 240°/s	150	169	11	Yes
Bowerman et al. [31]	18–25 yo college athletes	Extensors 60°/s	475.9 ± 133.8	522.96 ± 102.5	9	No
		Flexors 60°/s	519.3 ± 183.8	556.3 ± 139.7	7	No
Rozzi et al. [9]	College athletes	Extensors, 180°/s	338.2 ± 124.2	371.9 ± 154.7	9	No
		Flexors, 180°/s	214.7 ± 46.4	220.6 ± 51.8	3	No
Barber-Westin et al. [30]	9–10 yo athletes	Extensors, 180°/s	195 ± 93	162 ± 60	20	No
		Flexors, 180°/s	214 ± 74	183 ± 63	17	No
Noyes and Barber-Westin [58]	11–13 and 14–17 yo athletes	11–13 yo ER, 120°/s	274 ± 100	312 ± 216	12	No
		11–13 yo ER, 180°/s	257 ± 133	243 ± 153	6	No
		11–13 yo IR, 120°/s	270 ± 126	284 ± 157	5	No
		11–13 yo IR, 180°/s	242 ± 177	233 ± 130	4	No
		14–17 yo ER, 120°/s	284 ± 113	329 ± 126	14	No
		14–17 yo ER, 180°/s	209 ± 54	238 ± 130	12	No
		14–17 yo IR 120°/s	234 ± 84	323 ± 168	28	Yes
		14–17 yo IR, 180°/s	191 ± 155	266 ± 134	28	No
Wojtys et al. [18]	19–31 yo sedentary to elite athletes	Extensors 60°/s	412 ± 143	419 ± 123	2	No
		Flexors 60°/s	383 ± 157	488 ± 167	22	No

Data shown are mean ± standard deviation
Difference (%): % differences between groups in adjacent columns
Units for each result are reported in the first data point in male column and are representative of entire study cited
Difference significant? $P = 0.05$ between groups in adjacent columns
ER external rotation, *IR* internal rotation

6.4 Summary

There are gender differences in neuromuscular indices such as laxity, stiffness, strength (both knee and hip), H:Q ratios (particularly at high speeds), balance, and hamstring/quadriceps recruitment patterns. However, the influence of these differences on injury susceptibility remains unclear. This is due to a lack of a clear understanding of the multifactorial mechanism of ACL injuries, especially in the female population, with newer evidence pointing toward structural, mechanical, and neuromuscular factors. Continued research in neuromuscular control is justified because unlike many anatomical and physiological factors, it is modifiable.

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7

Neuromuscular Differences Between Men and Women

Timothy C. Sell and Scott M. Lephart

Abstract

Anterior cruciate ligament (ACL) injury prevention strategies have not always been successful. The identification of modifiable risk factors for injury is an important step in the injury prevention process. The gender differences observed in ACL injury rates pose an additional layer of complexity within this process; specifically, what are the sex-specific, modifiable risk factors for noncontact ACL injury? The identification of sex-specific risk factors for noncontact ACL injury facilitates the development of precise interventions. The purpose of this chapter is to outline the dynamic joint stability paradigm and provide an overview of the neuromuscular differences between men and women. The authors' studies have demonstrated that female athletes have decreased proprioception, compensatory neuromuscular control patterns, enhanced static balance, and decreased lower extremity strength compared with male athletes. These differences have resulted in altered neuromuscular control as observed in the kinematic and kinetic characteristics of the knee during dynamic tasks. Injury prevention and performance optimization must account for these differences, with specificity of training included to reduce the incidence of these debilitating ACL injuries.

7.1 Introduction

Athletes participating in a wide variety of sports are at risk of suffering significant joint injuries such as anterior cruciate ligament (ACL) rupture [1, 2]. ACL injury results in short- and long-term disabilities and includes the development of osteoarthritis that limits individuals from leading a healthy, active lifestyle [3–5]. Injury prevention strategies have not always been successful (at least in student-athlete populations), because the ACL injury rate has remained consistent for over 20 years [6–8]. This includes gender differences in ACL injury rates, a focus of this book [6–8]. Fittingly, a substantial research effort has been concentrated on the most effective injury prevention techniques, surgical protocols, and rehabilitation programs following ACL rupture [9–12].

The identification of modifiable risk factors for injury is the most important step in the injury prevention process (see Fig. 7.1) [13]. We have used this process effectively in a large military population to significantly reduce injuries [14].

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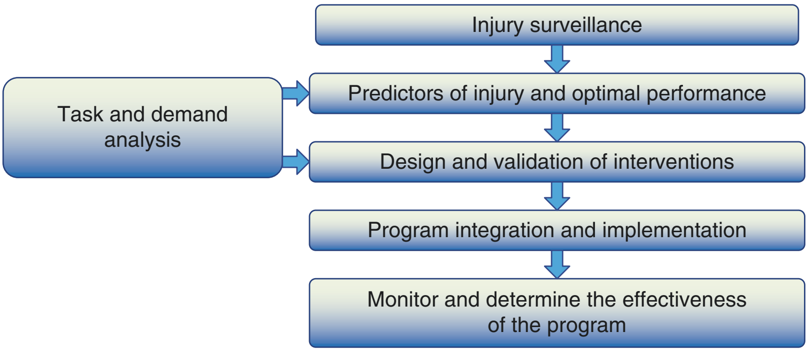


Fig. 7.1 Injury control process (From Sell TC, Abt JP, Crawford K, Lovalekar M, Nagai T, Deluzio JB et al. Warrior Model for Human Performance and Injury Prevention: Eagle Tactical Athlete Program (ETAP) - Part I. Journal of Special Operations Medicine. 2010;10(4):2–21)

The gender differences observed in ACL injury rates pose an additional layer of complexity within this process; specifically, what are the sex-specific, modifiable risk factors for noncontact ACL injury? The identification of sex-specific risk factors for noncontact ACL injury facilitates the development of precise interventions. Intervention strategies must be precise, that is, focus only on the characteristics and requirements necessary to reduce injury. Targeted and precise injury prevention is economical and efficient. It allows individuals to spend time and money on the wide range of needs necessary for care and training, which are particularly true in both student-athlete and military populations. The purpose of this chapter is to outline the dynamic joint stability paradigm and provide an overview of the neuromuscular differences between men and women. This overview will include an examination of gender differences in postural stability, muscle activation, strength, biomechanics, and the effects of fatigue on these same characteristics. The chapter will finish with a description of emerging research initiatives examining gender differences and point toward future research.

7.2 Dynamic Joint Stability and the Functional Joint Stability Paradigm

Dynamic joint stability is essential to safe and injury-free participation in sports, recreational activities, and exercise. This is particularly true at the knee because many activities place significant biomechanical demands on the lower extremity. Common athletic tasks such as stop-jump maneuvers require individuals to perform under joint loading forces that approach four times the athlete's body weight. Efficient and adequate dynamic knee stability is necessary to endure these high joint loading forces that can cause ligamentous injury [15–17]. Defined globally, stability is a state of remaining unchanged in the presence of forces that would normally change the state or condition [18]. From a physics perspective, stability can be compared to static equilibrium such that objects that remain in static equilibrium have met conditions where the sum of the forces and the sum of the moments are equal to zero (both external and internal) [19]. Joint stability can be defined as the state of a joint remaining or promptly returning to proper alignment through an equalization of forces [20]. It is a complex process that requires synergy between bones, joint capsules, ligaments, muscles, tendons, and sensory receptors [21].

The components of joint stability can be classified as either static or dynamic. The static components include the ligaments, joint capsule, cartilage, friction, and the joint bony geometry [22, 23]. The static components are typically assessed through joint stress testing and have commonly defined clinical joint stability [20]. The components provide the foundation for joint stability during functional activities by guiding joint arthrokinematics. However, the static components alone are not fully capable of providing the entire restraint necessary to prevent injury, especially during demanding tasks such as running, jumping, and cutting. The static components of joint stability work synergistically with the dynamic components of joint stability.

The dynamic components of joints stability include neuromuscular control of the skeletal muscles crossing the joint [20]. Dynamic joint stability is influenced by the neuromuscular control of the muscles crossing the joint. Neuromuscular control is the unconscious activation of the dynamic restraints occurring in preparation for and in response to joint motion and loading for the purpose of maintaining and restoring functional joint stability [20]. Neuromuscular control of joint stability involves a complex interaction between components of the nervous system and the musculoskeletal system and typically is accomplished through two different control systems: feedback and feed-forward control [24]. In a system that uses feedback control, sensors are continually measuring the parameter of interest based on an optimal value. A deviation from this optimal value will initiate an error signal. In response to this error signal, the system will trigger a compensatory response. Feed-forward systems also require measurement of a parameter, but measurement occurs only intermittently. The sensory components of this system are designed to measure a potential disturbance or change in the parameter of interest. Once a potential disturbance has been detected, the system initiates an error signal. In response to this error signal, the system institutes commands to counteract the anticipated effects of the disturbance. The commands instituted by this system are largely shaped by previous experience with similar disturbances. Feed-forward control systems are considered to be anticipatory compared to feedback control systems, which are characterized by responses only to current stimulus. Both are essential for optimal maintenance of dynamic knee stability.

The majority of research on ACL injuries and joint stability has focused on the ACL's primary role of restraining anterior translation of the tibia with respect to the femur [25]. The ACL also plays an important role in maintaining rotational stability (internal rotation [IR] and external rotation [ER] of the tibia on the femur) [26–28]. While the ACL acts as a primary restraint to anterior tibial translation, it also has a role in restraint to both valgus-varus and IR-ER rotation loading [29, 30]. Data that demonstrates the importance of the ACL in rotational stability includes the effect of injury on in vivo knee kinematics [31–33]. Using a dynamic stereo X-ray system, Tashman and colleagues demonstrated that there is approximately 10° of knee IR-ER during running [32]. After ACL injury, knee IR-ER range of motion and kinematics are altered [31, 33]. These altered kinematics may be associated with changes in the mechanical restraint that were previously provided by the ACL.

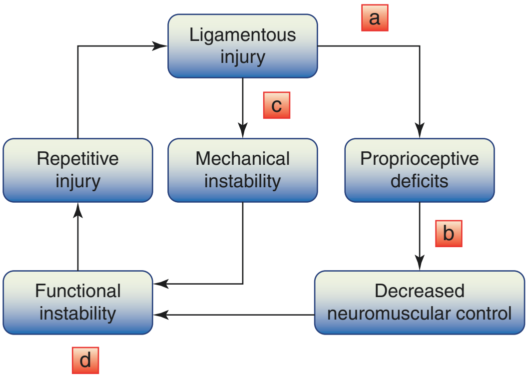


Fig. 7.2 Functional joint stability paradigm (From Lephart SM, Warner JP, Borsa PA, Fu FH. Proprioception of the shoulder joint in healthy, unstable, and surgically repaired shoulders. Journal of Shoulder and Elbow Surgery. 1994;3(6):371–80; and Lephart SM, Fu FH. Proprioception and neuromuscular control in joint stability. [Champaign, IL]: Human Kinetics; 2000)

The functional joint stability paradigm (see Fig. 7.2) was developed to demonstrate and provide a framework to examine the effects of injury, surgery, rehabilitation, and injury prevention on joint stability [34, 35]. It can also provide a framework to examine the effects of fatigue, pain, and neurocognitive changes observed following concussion. As originally described, the precipitating event (catalyst) is a ligamentous injury. This injury has a significant effect on the sensorimotor system, disruption of afferent information that previously arose from mechanoreceptors responsible for proprioceptive information (Fig. 7.2a). These proprioceptive deficits can lead to decreased neuromuscular control (Fig. 7.2b), which can be observed in altered activation (magnitude) and activation patterns (timing and coordination) of those muscles that provide the dynamic restraint (dynamic components of joint stability) for the joint. The combined effect of proprioceptive deficits and decreased neuromuscular control with a disruption (Fig. 7.2c) of a static component of joint stability (mechanical instability) leads to functional instability (Fig. 7.2d). While there are instances when an individual can maintain functional joint stability after ligamentous injury, the majority of individuals will demonstrate episodes of giving way and altered joint kinematics and kinetics. Often, individuals suffer repetitive or additional injury to other joint structures including other static components and dynamic components of joint stability.

ACL injury is an ideal model to demonstrate how the functional joint stability paradigm can be used for research, rehabilitation, and injury prevention. The primary role of the ACL is to restrain anterior translation of the tibia with respect to the femur [25]. This ligament also has important role in rotational stability (both IR-ER and valgus-varus) [28, 30, 36]. Injury to the ACL leads to both mechanical instability as measured by a knee arthrometer (examining movement of the tibia relative to the femur [37]) and proprioception [38, 39]. The subsequent effects of these proprioceptive deficits include altered neuromuscular control that, combined with mechanical instability, leads to functional instability [40–42]. There are instances when individuals can function safely and effectively without reestablishing (surgical repair of the ACL) the mechanical stability of the joint, but these instances are rare [43]. The goals of ACL reconstruction are to reestablish mechanical stability as well as restore proprioception (Fig. 7.2a, c) [44]. Rehabilitation focuses on reestablishing or improving proprioception in an attempt to improve neuromuscular control and improve functional joint stability [34, 45, 46]. Injury prevention strategies focus on maximizing proprioception, increasing strength, improving neuromuscular control, improving joint kinematics during demanding tasks to reduce joint loading, and developing movement strategies to dissipate and decrease landing forces (Fig. 7.2a, b, d) [47–54].

7.3 Proprioception

We define proprioception as the afferent information arising from the internal peripheral areas of the body that contribute to postural control, joint stability, and conscious sensations. These include the conscious submodalities of proprioception: joint position sense, active and passive kinesthesia, the sense of heaviness or resistance, and appreciation of movement velocity [55, 56]. As a component of the sensorimotor system (afferent sensory information, central processing and integration, and neuromuscular control), proprioception is essential in the maintenance of knee stability [57]. The role of the ACL is to resist anterior translation, valgus-varus, and IR-ER of the tibia on the femur [26–28]. Components of ACL (mechanoreceptors) provide afferent information essential to joint stability in addition to the mechanical stability that the ligament affords. Histological examination of the ACL has demonstrated the presence of several different mechanoreceptors including Ruffini endings, Pacinian corpuscles, Golgi-like receptors, and free nerve endings [58, 59]. Afferent information from these mechanoreceptors is integrated into the sensorimotor system and, when intact and functioning efficiently, contributes to safe and effective neuromuscular control of the lower extremity. However, any alterations in the acquisition, processing, and integration of proprioceptive information can impact functional joint stability and may result in injury.

Deficits in knee joint proprioception in female athletes may contribute to the increased rate of ACL injury because these deficits inhibit recruitment of the dynamic stabilizers that prevent anterior tibial translation. We previously examined the proprioceptive characteristics of male and female collegiate-level athletes [60]. Knee joint proprioception was measured by assessing threshold to detect passive motion (TTDPM) with a custom-built testing device that was capable of rotating the knee joint at 0.5°/s. The most important result of this study was that females demonstrated diminished proprioception when the knee was rotated from 15° of knee flexion toward full extension. We hypothesized that the decreased ability to detect motion toward a dangerous position [61–63] of full extension could interfere with the preactivation of protective muscle forces such as the hamstrings.

Given the rotation stability requirement at the knee, we designed a comprehensive study to examine the reliability, precision, and gender differences for TTDPM for IR-ER of the knee [64]. The dynamometer of a Biodex System 3 Multi-Joint Testing and Rehabilitation System (Biodex Medical Inc. Shirley, NY) was adapted and modified in order to incorporate the appropriate controls to eliminate visual, auditory, and tactile sensations that can confound results (Fig. 7.3). An air pneumatic boot (FP walker boots, Aircast, Summit, NJ) was modified so that it could be attached to the dynamometer. Each subject underwent four tests of TTDPM, two with the knee in a position of IR and two with the knee in a position of ER (Fig. 7.4). For each position, the knee was rotated toward IR and ER. Subjects were asked to notify the examiner via a switch when motion occurred and in what direction it occurred. Repeated measures demonstrated that each TTDPM test had good reliability and precision. Gender comparisons revealed that female athletes had diminished proprioception when the knee was rotated internally from both starting positions of IR and ER. Similar to movement toward full extension as observed previously, movement toward full IR loaded the ACL [28].

It may be theorized that diminished proprioception negatively affects neuromuscular control and potentially put females at greater risk for noncontact ACL injury. Unfortunately, little evidence exists that demonstrates a relationship between proprioception and neuromuscular control. We have examined these relationships and recently demonstrated a significant relationship between TTDPM and joint kinematics during an athletic task [65]. The relationship between knee flexion angle at landing, knee flexion/extension TTDPM, and strength was examined in a population of 50 physically active male adults (mean age, 26.4 ± 5.8 years). The subjects underwent TTDPM testing (knee flexion/extension), knee flexion/extension strength testing with an isokinetic dynamometer (Biodex Medical Inc., Shirley, NY), and a kinematic analysis during a single-leg stop task. Pair-wise correlation coefficients demonstrated that individuals who had better TTDPM in the direction of knee flexion and knee extension landed with greater knee flexion at initial contact with the ground.

We have continued to examine the role of proprioception in functional joint stability, especially

Fig. 7.3 Knee internal/external TTDPM setup (From Nagai T, Sell TC, Abt JP, Lephart SM. Reliability, precision, and gender differences in knee internal/external rotation proprioception measurements. Phys Ther Sport. 2012;13(4):233–7)

as it relates to gender and noncontact ACL injury [66, 67]. In the first of these studies, Clark et al. examined predictors of knee joint stability in uninjured physically active adults [66]. As part of this study, a new measure of active joint position sense (AJPS) was developed to provide greater clinical insight [68]. Reliability and precision were excellent for this measure that included eccentric-to-isometric hamstring-biased AJPS measured in a prone position. No differences in AJPS were observed between genders (see Fig. 7.5). In the second study, Keenan et al. measured trunk proprioception AJPS during a stop-jump maneuver [67]. The regression analysis revealed that trunk proprioception was not a significant predictor of knee kinematics.

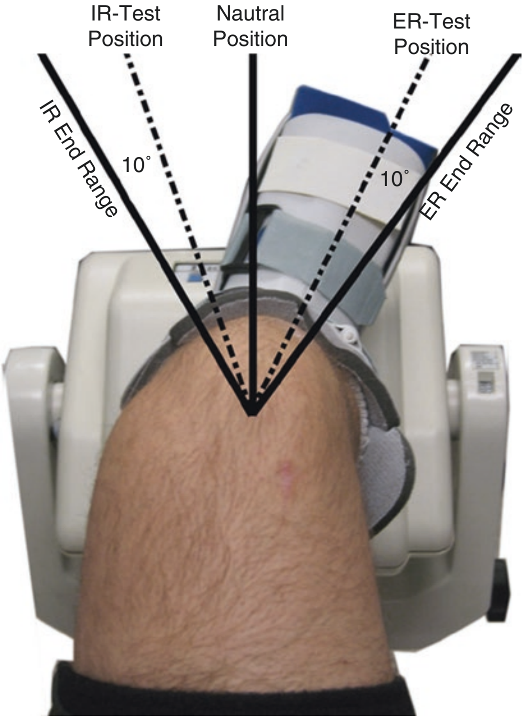
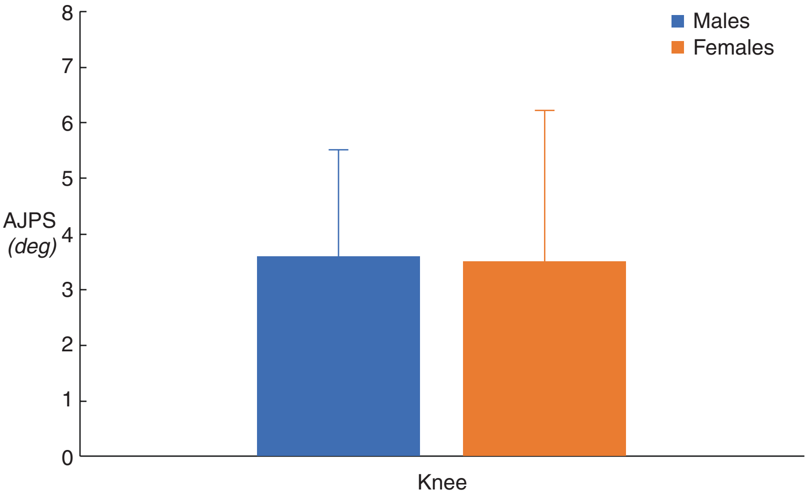


Fig. 7.4 Knee internal/external TTDPM positions (From Nagai T, Sell TC, Abt JP, Lephart SM. Reliability, precision, and gender differences in knee internal/external rotation proprioception measurements. Phys Ther Sport. 2012;13(4):233–7)

7.4 Postural Stability

Maintenance of postural stability is essential for activities of daily living, work, and athletic activities. Postural stability is frequently measured in athletic populations and in sports medicine research. It has been demonstrated to be a predictor of performance [69], is compromised after lower extremity musculoskeletal injuries [70, 71], is used in injury prevention training programs [72–75], and has been analyzed to determine risk factors for lower extremity injury [60, 76–82]. Postural stability has been defined as the ability to keep the body in equilibrium by maintaining the projected center of mass within the limits of the base of support [83]. Postural stability is often measured in research related to knee injuries since many of the same components

Fig. 7.5 Active joint position sense (From Clark NC, Lephart SM, Abt JP, Lovalekar M, Stone DA, Sell TC. Predictors of Knee Functional Joint Stability in Uninjured Physically Active Adults [Dissertation]. University of Pittsburgh: University of Pittsburgh; 2014



necessary for maintenance of postural stability are also necessary for dynamic joint stability. Both require establishing an equilibrium between destabilizing and stabilizing forces [84] and require sensory information from vision, the vestibular system, and somatosensory feedback [20, 85]. Postural stability is sometimes measured in studies designed to examine proprioception, but postural stability is not a measure of proprioception.

Postural stability is typically measured under two wide-ranging testing modes, static and dynamic. We define static postural stability as maintaining steadiness on a fixed, firm, unmoving base of support [86]. Typically, this is measured while an individual attempts to maintain a steady state (remaining as motionless as possible) while standing on one or two legs [87]. Dynamic postural stability has been defined as the ability to transfer the vertical projection of the center of gravity around the supporting base [87]. Another definition is the ability to maintain postural stability under changing conditions such as change in the support surface [88], following a perturbation of the individual [89, 90], or after a change in position or location such as during a single-leg jump or landing [86, 91, 92]. Dynamic postural stability has been measured with a multiple single-leg hop-stabilization test [86], a time to stabilization test [91], the star-excursion test [93], and the dynamic postural stability index (DPSI) [92]. We have examined the correlation between static and dynamic measures of postural stability [94]. The goal was to determine what measure of postural stability has the best discriminatory capability in order to predict risk of injury, especially in athletic populations. The results of this study demonstrated that static measures of postural stability as measured with single-leg static balance measures (eyes open and eyes closed) do not correlate with two dynamic measures of postural stability: anterior-posterior jump and medial-lateral jump (measured with the DPSI).

Gender comparisons in static postural stability measures provide additional evidence supporting the need to examine dynamic postural stability measures. We have examined differences in static postural stability between genders in high school athletes, college athletes, and military personnel [13, 60, 95–97]. Females demonstrated better static postural stability than males across all of these populations. We examined single-leg balance (eyes open and eyes closed) in male and female basketball players using a protocol based on Goldie et al. [87, 98]. Females demonstrated significantly better single-leg balance scores for both conditions [97]. Our research in collegiate athletes (National Collegiate Athletic Association [NCAA] Division I) using the Biodex Stability System (Biodex, Inc., Shirley, New York) [60] demonstrated that female athletes had a significantly better stability index then their male counterparts. We have completed a series of studies examining injury prevention and performance optimization with the US Army's 101st Airborne Division (Air Assault) in Ft. Campbell, KY [13]. Tactical athletes such as these soldiers suffer similar unintentional musculoskeletal injuries as civilian athletes. Static postural stability was assessed using a protocol similar to our study with high school basketball players [13, 95, 96]. Female soldiers demonstrated better static postural stability than male soldiers (lower values represent better postural stability; Fig. 7.6). The results of these three studies appear to contradict the fact that females suffer ACL injuries at a higher rate than their male counterparts in similar sports and also demonstrate diminished proprioception. Additionally, single-leg balance deficits have not been identified as a risk factor for primary ACL injury, which indicates the need for postural stability testing that presents a greater challenge to the sensorimotor system.

The DPSI has become a common measure to examine postural stability in athletic populations. Typically, the DPSI is measured during a landing task after jumping over an obstacle or after jumping a measured height [92, 94] and requires the individual to stabilize as quickly as possible after the landing. It may be a more appropriate challenge for healthy, athletic populations [94]. Previous studies have used the DPSI to examine differences between genders with mixed results [99, 100]. Both Wikstrom

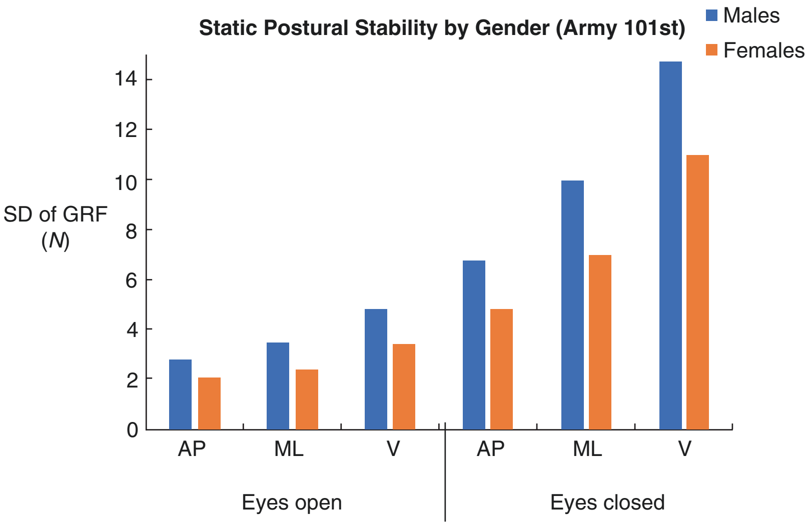


Fig. 7.6 Static postural stability in military personnel. Lower values represent better postural stability. *AP* anterior-posterior, *ML* medial-lateral, *V* vertical, *SD of GRF* standard deviation of ground reaction forces (From Sell TC, Abt JP, Crawford K, Lovalekar M, Nagai T, Deluzio JB et al. Warrior Model for Human Performance and Injury Prevention: Eagle Tactical Athlete Program (ETAP) - Part I. Journal of Special Operations Medicine. 2010;10(4):2–21)

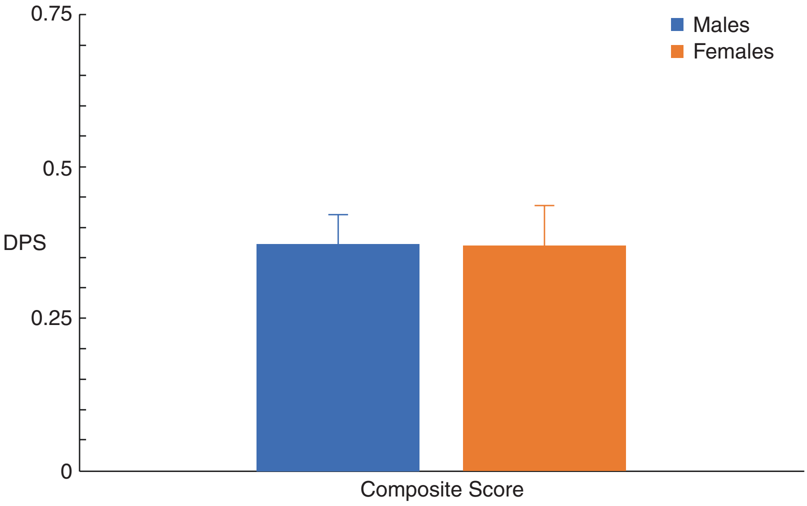


Fig. 7.7 Dynamic postural stability in military personnel (From Sell TC, Lovalekar MT, Nagai T, Wirt MD, Abt JP, Lephart SM. Gender Differences in Static and Dynamic Postural Stability of Soldiers of the Army's 101st Airborne Division (Air Assault). J Sport Rehabil. 2017:1–20)

et al. and Dallinga et al. examined gender differences during a landing task while calculating the DPSI [99, 100]. Wikstrom et al. examined an anterior-posterior jump and revealed that females had worse scores than males [100]. In contrast, Dallinga et al. demonstrated that males had inferior scores than females during similar dynamic postural stability testing [99]. Our own research in a military population (Fig. 7.7) demonstrated no differences between genders for dynamic postural stability during an anterior-posterior jump [96].

We recently completed a study designed to challenge rotational stability of the knee (transverse plane) during a landing task [101]. The task was identical to a traditional DPSI assessment except individuals were required to rotate 90° in the air prior to landing. Between-day reliability

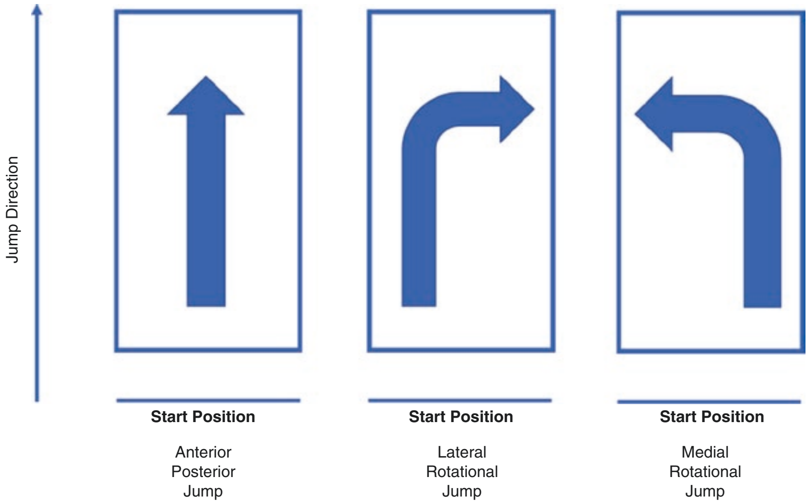


Fig. 7.8 Different jump directions for the dynamic postural stability index (From Sell TC, Heebner NR, Pletcher ER, Lephart SM. Reliability and Hamstring Activation during Rotational Dynamic Postural Stability in Healthy Recreational Athletes. The 2015 American Physical Therapy Association's Combined Sections Meeting; February 4–7, 2015; Indianapolis, IN 2015)

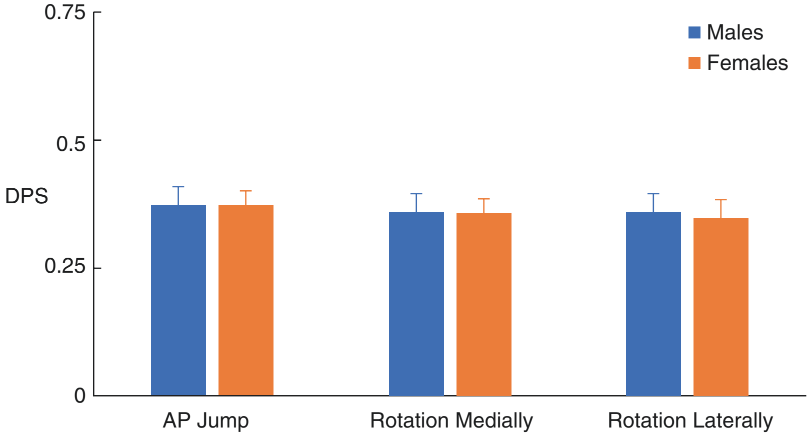


Fig. 7.9 Dynamic postural stability index across different jump directions (From Sell TC, Heebner NR, Pletcher ER, Lephart SM. Reliability and Hamstring Activation during Rotational Dynamic Postural Stability in Healthy Recreational Athletes. The 2015 American Physical Therapy Association's Combined Sections Meeting; February 4–7, 2015; Indianapolis, IN 2015)

of the rotational jump was high. There were differences between the rotational jump and the traditional anterior-posterior jump in joint biomechanics, potentially indicating a greater challenge to rotational joint stability. Gender comparisons were made across multiple jumps, including an anterior-posterior jump and the two rotational jumps (Fig. 7.8). Subjects were healthy, recreationally active, college students. No significant differences were observed for any of the jump directions for dynamic postural stability (Fig. 7.9).

7.5 Electromyographic Activity

The electromyogram (EMG) represents the electrical manifestation of the contracting muscle [102] as it transmits from the neuromuscular junction along the muscle fiber [103]. Measurement of EMG activity provides information regarding the amount of electrical activity in the contracting muscle, which in turn provides insight into the magnitude of tension developed [104]. Relative to the functional joint stability paradigm (Fig. 7.2), EMG can describe neuromuscular control as well as the attempt to maintain functional joint stability (or inability to maintain functional joint stability). Unfortunately, many variables can influence this signal which creates difficulty in interpreting these data. A direct comparison between activation levels and force production is generally not recommended. However, muscle activation patterns, amplitude, and quantity provide important insight into the neuromuscular control of joint stability.

Dynamic knee stability is dependent on the neuromuscular control over the musculature of the knee in order to reduce strain in the ACL. In order for this control to be effective, the central nervous system (CNS) must be able to anticipate destabilizing forces and act appropriately [105]. Benvenuti et al. examined EMG activity of upper arm musculature during reaction-time arm movements. These investigators demonstrated that, when destabilizing forces were anticipated, the CNS was capable of adjusting muscle activation patterns to oppose these forces. These findings support the belief that anticipatory postural adjustments are planned in detail [106]. Studies have conducted gender comparisons of EMG activity of the knee musculature during athletic tasks to quantify the role of the knee extensors and flexors in dynamic knee stability [107–109].

We have previously examined EMG activity of knee in order to determine differences between genders in dynamic stabilization strategies [60], to examine the demands of different athletic tasks [110], to determine differences between planned and reactive tasks [110], and to determine predictors of proximal anterior tibia shear force [111]. Rozzi and colleagues demonstrated that female collegiate-level soccer players activated the lateral hamstrings differently than male players during a drop-landing task. Females had a greater peak amplitude and integrated EMG (IEMG) for lateral hamstrings in response to the landing. We concluded that this finding represented an attempt by female athletes to prevent anterior tibial translation that occurs during this task. Similar observations were made in male and female high school basketball players while they performed planned and reactive stop-jump tasks [110]. Reactive tasks were included to better simulate actual athletic conditions when athletes have to react quickly to other competitors. Female high school basketball players demonstrated greater IEMG activity of the semitendinosus and a higher co-contraction value during the 150 ms prior to the initial landing compared with male players for planned and reactive tasks. These gender differences observed in semitendinosus activity during stop-jump tasks are consistent with a previous study [60] and reinforce the concept that females use compensatory strategies to counter decreased knee joint proprioception in order to achieve functional joint stabilization.

We continue to analyze EMG relative to female athletes and knee injuries. EMG activation patterns, timing, amplitude, and quantity provide insight into the attempt to achieve function joint stability in the presence of destabilizing forces and moments. In our most recent study, we determined if EMG of the medial hamstrings muscle group predicted performance during a single-leg stop-jump task [66]. We examined preactivity and reactivity (relative to initial contact) and examined its relationship to valgus-varus displacement. Preactivity explained a small, but significant, percentage of the variance in valgus-varus displacement during the single-leg stop-jump task. No gender differences in muscle activity were observed.

7.6 Strength

The dynamic components of joint stability are dependent on the characteristics and capabilities of the muscles crossing the joint [20]. One of the more important capabilities is muscular strength (force production). Muscular strength represents the ability of an individual to produce the internal muscles to counteract the destabilizing forces that occur during dynamic activities. The primary dynamic stabilizers of the knee joint are the knee flexors (hamstrings) and the knee extensors (quadriceps). Both of these muscle groups influence strain on the ACL such that an increase in hamstrings activity can reduce the amount of strain, whereas an increase in quadriceps activity can increase the amount of strain [112, 113].

Individuals with insufficient muscle strength, muscular imbalance, or inadequate activation levels and timing may not have the capability to counteract the destabilizing forces during dynamic tasks.

Our research has consistently demonstrated that males have significantly greater strength than females. Male Division I NCAA volleyball, basketball, and soccer athletes have significantly stronger knee extension and flexion strength compared with females of similar age and activity level [114]. Similar differences between genders in isokinetic knee strength have also been observed between male and female high school basketball players [97]. Strength comparisons between male and female soldiers of the 101st Airborne (Air Assault) Division have also been performed [13]. Similar to civilian athletes, male soldiers demonstrate significantly greater isokinetic knee extensor and flexor strength than female soldiers (Fig. 7.10) [95]. In addition to tradition strength measures, we have also examined time-to-peak torque [66] which represents the amount of time between the initiation of a test and maximum (or peak) torque production. Females take longer to develop peak torque production then their male counterparts (Fig. 7.11).

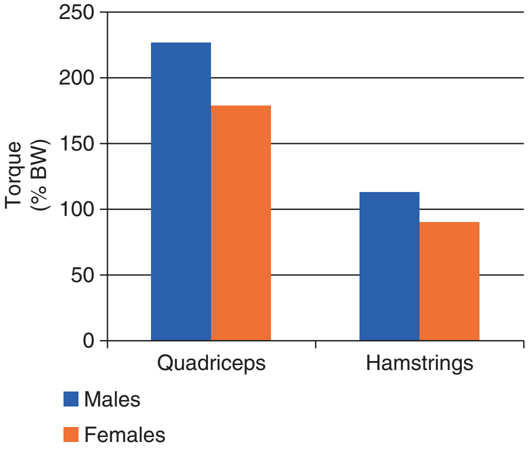


Fig. 7.10 Hamstrings and quadriceps strength in military personnel (From Allison KF, Keenan KA, Sell TC, Abt JP, Nagai T, Deluzio J et al. Musculoskeletal, biomechanical, and physiological sex difference in the US military. Army Medical Department Journal. 2015;April–June:22–32)

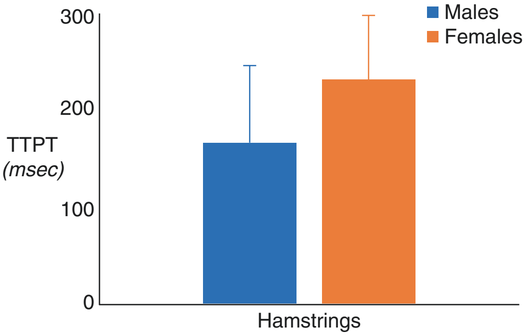


Fig. 7.11 Hamstrings time-to-peak torque (From Clark NC, Lephart SM, Abt JP, Lovalekar M, Stone DA, Sell TC. Predictors of Knee Functional Joint Stability in Uninjured Physically Active Adults [Dissertation]. University of Pittsburgh: University of Pittsburgh; 2014)

While strength testing as measured by force output is an important characteristic of the dynamic stabilizers of the knee joint, a more relevant measure for injury risk may be the hamstrings-to-quadriceps (H-Q) strength ratio. Myer and colleagues prospectively demonstrated that females who suffered ACL injury had a lower H-Q strength ratio compared with female controls and male controls who did not suffer ACL injury [115]. These investigators also demonstrated that females who subsequently suffered an ACL injury had lower hamstring strength, but not lower quadriceps strength, compared with males who did not suffer an ACL injury. Our studies have consistently demonstrated that females and males have similar H:Q strength ratios when using similar isokinetic speeds (Fig. 7.12). It is important to note that our studies represent comparisons between uninjured male and female groups.

We have examined isometric IR-ER strength in male and female athletes, as well as the relationship between knee flexion/extension strength and landing kinematics [65]. Internal and external isometric strength was measured with a similar setup as described with TTDPM testing. Female athletes demonstrated lower IR and ER strength compared with male athletes (Fig. 7.13). These results are consistent with other gender comparisons in knee strength. Nagai and colleagues also demonstrated a significant relationship between knee extension strength and knee

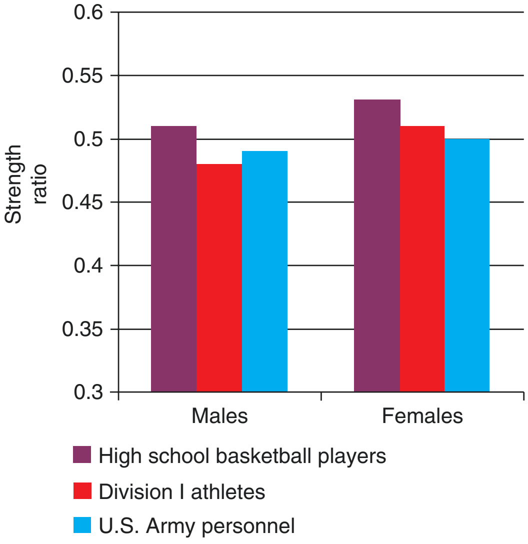


Fig. 7.12 Hamstrings-quadriceps strength ratios across athletes and military personnel

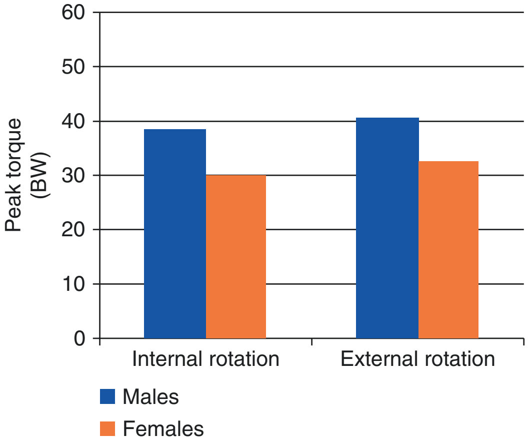


Fig. 7.13 Knee internal/external rotation strength

flexion angle on landing; as quadriceps strength increased, so did knee flexion angle at initial contact [65]. In terms of ACL injury, landing in a more flexed position is safer than landing in an extended position [28, 116, 117]. Isolated knee strength measurements only describe the force production capabilities of the movements tested. Combining knee strength testing with other measures of functional joint stability such as landing kinematics, and examining the relationship between each, gives a better picture of the interaction between the variables and provides insight into strategies of maintenance of functional joint stability.

7.7 Biomechanics

The functional joint stability paradigm (Fig. 7.2) demonstrates that deficits in proprioception, EMG activity, and strength may affect neuromuscular control and knee joint stability. Neuromuscular control and knee joint stability may be further examined through motion analysis and calculation of relevant knee biomechanical variables such as joint kinematics and joint kinetics. We have examined the biomechanics of males and females performing several different tasks in order to determine how neuromuscular control (deficits) affects landing kinematics and kinetics. These studies demonstrated that female athletes typically land with greater vertical ground reaction forces, greater peak posterior ground reaction forces, greater proximal anterior tibia shear force, increased hip internal rotation, less knee flexion, and greater knee valgus compared to their male counterparts [110, 114]. Our research with the military includes gender comparisons between male a female soldiers of the 101st Airborne (Air Assault) Division while performing a vertical drop-landing task. We analyzed the valgus-varus position of the knee at initial contact for each task. Females performed the vertical drop-landing task in greater valgus than males [95]. While males landed in a varus position, females landed relatively close to neutral valgus-varus position (Fig. 7.14).

Measurement of knee biomechanics continues to be an important aspect of assessing functional joint stability. We have begun to examine different instrumentations to measure knee biomechanics that does not depend on brick-and-mortar research laboratories. We are currently comparing three-dimensional accelerations of the tibia measured with skin-mounted accelerometer to knee joint forces measured through inverse dynamics and tibial acceleration and translation compared with dynamic stereo X-ray system. Current research has been expanded to

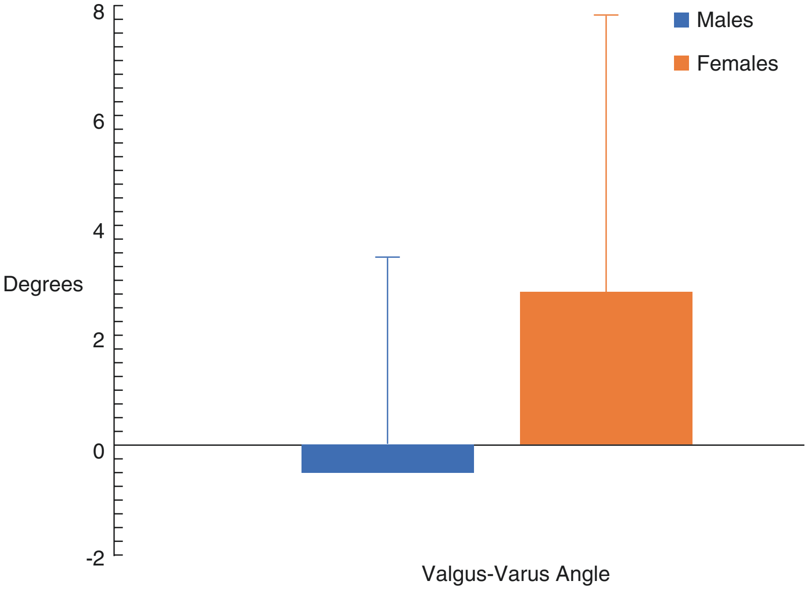


Fig. 7.14 Knee valgus-varus angle during a vertical drop landing (From Allison KF, Keenan KA, Sell TC, Abt JP, Nagai T, Deluzio J et al. Musculoskeletal, biomechanical, and physiological sex difference in the US military. Army Medical Department Journal. 2015;April–June:22–32)

incorporate emerging technology, including the use of wireless three-dimensional inertial sensors that have the potential to be used during actual competition. The ultimate goal of this research is to develop robust but portable instrumentation to collect relevant biomechanical data away from traditional laboratory environments.

7.8 Fatigue

Fatigue creates an environment in which more musculoskeletal injuries occur, whether it is within a single game/competition or within a series of closely scheduled games [118–124]. These observations include muscular injuries, joint injuries, and noncontact ACL injuries [125]. Muscular fatigue can disrupt or degrade the compensatory stabilizing mechanisms necessary to maintain joint stability in the presence of destabilizing forces and moments [80]. Although the exact mechanisms are unclear, the disruption of normal stabilizing mechanisms may decrease neuromuscular control [126, 127], increase knee joint laxity [80, 128, 129], decrease balance skill [126], and decrease proprioception [130–133]. We have conducted several studies examining the effects of fatigue on neuromuscular and biomechanical characteristics.

We have examined knee joint laxity, kinesthesia (via TTDPM), lower extremity balance, and surface EMG activity during a landing maneuver of male and female athletes before and after a peripheral muscular fatigue protocol [80]. The protocol was designed to induce fatigue of the knee flexors and extensors and was implemented using a Biodex isokinetic dynamometer. Peripheral fatigue decreased the time to detect motion, increased the contraction onset time after landing for the medial hamstrings and gastrocnemius, and increased IEMG of the vastus lateralis and vastus medialis after landing. Both males and females were affected equally. We have also demonstrated fatigue, induced by an exhaustive run [134, 135], forces adaptations in landing kinematics equally in both genders [136]. Both male and female recreational athletes demonstrated a decreased knee flexion angle at initial contact and a decreased maximum valgus angle which were theorized to be an attempt to promote knee stability. Overall, it appears that fatigue affects both genders equally and places both male and female athletes at greater risk for injury.

We have conducted several studies regarding the relationship between physiological characteristics such as anaerobic capacity, aerobic capacity, and muscular endurance to determine the effects of fatigue on neuromuscular and biomechanical risk factors for injury. During a pilot study, we induced fatigue using a maximum oxygen uptake treadmill test and a test of anaerobic power and capacity. Both protocols significantly affected postural stability during a single-leg balance task that persisted for 8 min. We recently completed a study examining the effects of fatigue (whole body exercises and multiple bouts of running) on knee proprioception measured by TTDPM [137]. Fatigue was verified through ratings of perceived exertion, heart rate, and blood lactate measures. No changes in proprioception were observed post-fatigue, but there was a significant relationship between aerobic capacity and proprioception that may indicate highly trained individuals have better proprioception.

Fueling, or feeding, is one potential intervention to prevent the onset of fatigue and its potential as a risk factor for noncontact ACL injury. We examined the effects of carbohydrate-electrolyte feedings on knee biomechanics and dynamic postural stability during intermittent high-intensity exercise to fatigue [138]. The fatigue protocol was designed to simulate a basketball game, including timing of quarters and physical activities performed. Fatigue induced changes in landing biomechanics such as knee flexion angle at initial contact during single-leg jump landings and dynamic postural stability. The feeding used in this study had little to no effect on knee biomechanics or dynamic postural stability. Nutrition and physical training and their relationship to fatigue-induced risk factors for noncontact ACL injury are an important area of research; however, few research studies have examined these interventions to date. Both nutrition and physical training strategies may be important to examine more closely in the future.

7.9 Current Research and Emerging Concepts

We continue to study gender differences between males and females in athletic and military populations, focusing on reducing the risk of injury as well as optimizing human performance. These objectives are not mutually exclusive, as improving performance and reducing injury risk can be accomplished simultaneously. This is especially true in environments where fatigue impacts injury risk. Performance optimization solely focusing on fitness (aerobic and anaerobic) can significantly impact injury risk [139]. Our research with the military, specifically examining the different injury risk profiles, task requirements, and demands of different mission types, demonstrates an increasing need for specificity of training relative to the physiological, musculoskeletal, and neuromuscular demands. We should not discount the role of the CNS in injury prevention. There is a mounting body of evidence indicating that brain injuries such as sports-related concussions increase the risk of injury [140–145]. This risk factor seems to be gender neutral. We are examining sports-related concussion as a risk factor for lower extremity injury in an attempt to develop a measurement or assessment tool to be added to medical clearance guidelines for return-to-play following concussion. This tool would screen for risk of lower extremity injury. Finally, the reinjury rate after ACL reconstruction is approaching 30% [146]. There is a critical need to develop better decision guidelines for this population and potentially explore if females require different rehabilitation strategies.

7.10 Summary

The functional joint stability paradigm provides the framework for mechanistic studies examining neuromuscular differences between men and women. The injury prevention process provides the steps to conduct high quality injury prevention research. Our studies have demonstrated that female athletes have decreased proprioception, compensatory EMG patterns, enhanced static balance, and decreased lower extremity strength compared with male athletes. Some of these same differences have also been observed in female military personnel. These differences have resulted in altered neuromuscular control as observed in the kinematic and kinetic characteristics of the knee during dynamic tasks. Injury prevention and performance optimization must account for these differences with specificity of training to reduce the incidence of debilitating ACL injuries.

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8 Effects of Alterations in Gait Mechanics on the Development of Osteoarthritis in the ACL-Deficient Knee

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Abstract

This chapter discusses the early development of knee osteoarthritis with regard to ACL injury. In addition, the kinematic and kinetic changes in the knee after ACL injury are summarized. The interaction between altered joint kinematics and the structural and biological components of articular cartilage is explored as an initiating mechanism of premature cartilage degradation following ACL injury.

8.1 Introduction

Tibiofemoral osteoarthritis (OA) occurs in a substantial and continually increasing portion of men and women who are greater than 50 years of age [1, 2]. The rising prevalence of knee OA is not just apparent among older individuals but in younger individuals as well. In particular, young athletes who have sustained an anterior cruciate ligament (ACL) rupture have a substantial risk of early development of knee OA [3–7]. Studies have shown that within 12–14 years of the index ACL injury, 41–56% of individuals demonstrate radiographic evidence of OA, and 50–75% report symptoms of knee OA [5, 7]. Reconstruction of the ACL does not appear to protect against the development of OA, as the odds of OA are no different in some studies between individuals with reconstruction versus those treated conservatively [5, 7]. A matched-pair analysis of ACL-injured high-level athletes with and without ACL reconstruction 10 years after the index injury showed no significant differences in the presence of radiographic OA between those who had a single-incision transtibial bone-patellar tendon-bone reconstruction (48%) and those who were treated conservatively (28%) [8]. Only 4% of the contralateral knees showed radiographic OA. A 10–15 year prospective study of ACL injury reported a 62% prevalence of knee OA in patients with isolated ACL injuries and an 80% prevalence in those with concomitant injuries [9]. Across various study methodologies and operational definitions, the findings from these studies highlight the significance of the development of knee OA after ACL injury. Despite the significance of early development of posttraumatic knee OA, the details of its early development are not well understood, and few modifiable risk factors have been identified [10]. As discussed in Chap. 4, concomitant meniscal injury requiring a meniscectomy is known to have a detrimental

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effect. In an 11–17 year follow-up of ACL-reconstructed patients, radiologic evidence of OA was present in 37% of those who had medial meniscectomies versus only in 11% of those with intact menisci [11].

Cellular, animal, simulated, and observational studies indicate that altered joint kinematics associated with the ACL-deficient or ACL-reconstructed knee may contribute to degenerative changes. Altered knee joint motion is observed immediately following ACL injury [12–15], whereas degenerative changes in cartilage and other joint structures are observed years following the injury [3–7]. It has been hypothesized that the altered kinematics following ACL injury transfer joint loads from frequently loaded cartilage areas to infrequently loaded cartilage areas, which over time contribute to degradation of the meniscus and articular cartilage [12, 13, 15–18].

In this chapter, the kinematic and kinetic changes in the knee after ACL injury will be discussed. The interaction between altered joint kinematics and the structural and biological components of articular cartilage will be explored as an initiating mechanism of premature cartilage degradation following ACL injury.

Critical Points

- The etiology of posttraumatic knee OA is not well understood.
- Prevalence of premature knee OA is high following ACL injury, regardless of whether graft reconstruction is performed.
- Altered joint motion associated with the ACL-deficient or ACL-reconstructed knee precedes degradative changes in the cartilage and meniscus structures, leading to the hypothesis that altered kinematics may be a causative factor in OA after ACL injury.
- Meniscus preservation substantially lowers the risk of future OA.

8.2 In Vivo Kinematic Changes Associated with ACL Functions

Evidence regarding the in vivo kinematic changes associated with ACL injury has emerged over the past two decades through a variety of investigational approaches consisting of primarily animal models, human motion analysis, and radiographic studies. The combined results of these studies offer compelling insights into the mechanistic link between kinematic changes following ACL injury and the initiation of cartilage degradation. Findings from studies of repetitive and routine joint-loading activities (such as walking) shed light on the development of OA as a gradual degenerative process.

During the normal human stride, the ACL functions primarily to provide anterior-posterior translational stability and internal-external rotational stability of the tibiofemoral joint. Important differences exist in the tibiofemoral motion of ACL-deficient knees compared to uninjured contralateral knees or healthy controls [12, 13]. During the stance phase of walking, displacement of the tibia in ACL-deficient knees is offset toward internal rotation and posterior translation compared to contralateral knees [12, 13]. Specifically, Andriacchi and Dyrby [12] found that the magnitude of the internal rotational offset correlated with the magnitude of the external knee flexion moment during the weight acceptance phase of gait. Further, increased flexion moments during weight acceptance were associated with the anterior-posterior offset in the ACL-deficient knees. In ACL-reconstructed knees, the average knee center of rotation, a multidimensional metric of knee kinematics, was more lateral and anterior compared to contralateral knees at 2 years postoperatively [19]. Between 2 and 4 years post-reconstruction, the average knee center of rotation shows progressive improvement toward kinematic symmetry with the contralateral limb for most participants [19]. Persistent abnormal knee center of rotation is associated with worsening clinical outcomes over time [19]. These observed offsets in motion have been corroborated by studies of other activities using radiographic techniques, including stereoradiography [20], fluoroscopy [21], and magnetic resonance imaging (MRI) [22–24]. During a quasi-static lunge activity, the tibia maintains an internally rotated position during low knee flexion angles in the ACL-deficient knee [21]. Following ACL reconstruction, studies of walking and downhill running have observed the tibia maintaining a position of greater external rotation [18, 20]. Although the axial position of the reconstructed knee appears to be opposite that of the ACL-deficient knee, the complete body of literature on the topic consistently indicates that an ACL injury leads to altered kinematics regardless of the choice to reconstruct the ligament. Meniscal status may exacerbate this effect, as meniscectomy has been shown to influence knee kinematics as well. In an in vivo study of medial meniscectomy in patients without ACL pathology, Netravali et al. observed a significant external tibial rotation offset in post-meniscectomy knees relative to the healthy contralateral knees [25]. This pattern is similar to kinematic changes in ACL-reconstructed subjects [18, 20]. Two indicators of medial knee joint loading, external knee adduction moment and impulse, were no different between individuals with isolated ACL injury and reconstruction and those with ACL reconstruction and concomitant meniscal pathology at 1–2 years post-surgery [26]. Further study is warranted to understand how meniscectomy interacts with ACL reconstruction in terms of the development of posttraumatic knee OA.

Recent work highlights the influence of surgical technique, specifically graft placement, on post-reconstruction knee kinematics. From the anterior tibia, the native ACL courses posterior, superior, and lateral, resisting anterior displacement [27] and internal rotation [28] of the tibia on the femur. Failure to restore anatomic obliquity of the graft in femoral tunnel placement (Fig. 8.1) can result in a knee with adequate sagittal stability but inadequate rotational stability [29, 30]. Abebe et al. [31] investigated the impact of two different femoral tunnel placements on tibiofemoral kinematics. In the "anteroproximal group," the femoral tunnel was placed near the anterior and proximal border of the ACL, while in the "anatomic group," the femoral tunnel approximated the center of the ACL. The anteroproximal group demonstrated up to 3.4 mm greater anterior tibial translation, up to 1.1 mm more medial translation, and up to 3.7° greater internal rotation compared with the anatomic group. A growing body of work [17, 32] also indicates that graft placement plays a critical role in the restoration of normal gait mechanics following reconstruction. In a study of 17 individuals with unilateral ACL reconstruction, Scanlan et al. [17] observed that a more vertical coronal orientation of the graft was associated with reduced peak external knee flexion moments, indicative of reduced net quadriceps muscles usage during walking. Alterations in gait mechanics, related to anterior femoral translations, tibial rotation motion, and knee extension motion, have been reported with both transtibial and anteromedial portal reconstruction techniques [33, 34]. Recent modeling work indicates that modulating graft properties, such as optimizing graft stiffness and pre-strain, may restore joint motion and cartilage stresses to closer to healthy knees [35]. Graft placement and properties, muscle function, and tibiofemoral kinematics likely interact in a manner that precipitates cartilage degradation in the ACL-deficient and ACL-reconstructed knee.

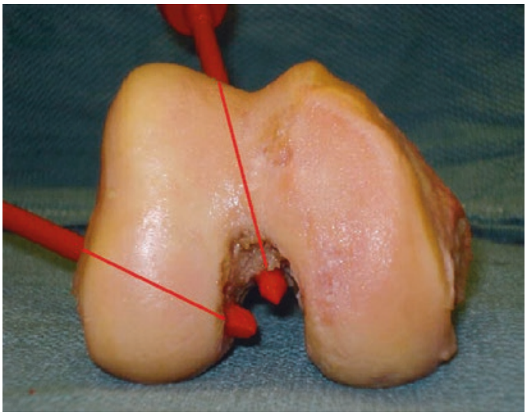

Fig. 8.1 Notch view of a dissected femoral specimen showing range of coronal obliquity between vertical and maximally oblique femoral tunnels (Reproduced with permission from Bedi et al. [29])

Critical Points

- Evidence during activities of daily living indicate consistent tibiofemoral kinematic changes following ACL injury.
- ACL-deficient knees exhibit greater tibial internal rotation and posterior translation compared to intact and uninjured knees, while ACL-reconstructed knees exhibit greater tibial external rotation compared to intact knees.
- Altered rotational tibiofemoral joint motion is thought to alter cartilage loading in a manner that initiates early cartilage degeneration.
- Medial meniscectomy also leads to greater tibial external rotation compared to intact knees, which may exacerbate the effects on cartilage loading.

8.3 Interaction Between Kinematics, Cartilage Metabolism, and Cartilage Structure

Animal models of OA after ACL transection implicate altered joint motion as a contributing factor to the initiation of OA [36–38] and are informative of the metabolic changes that are associated with ACL injury [39–41]. Following ACL injury, loss of proteoglycan content and changes in matrix metalloproteinase content are thought to contribute to progressive erosion of the cartilage that leads to OA [39–41]. However, animal models indicate that these progressive metabolic changes occur in conjunction with the altered mechanical joint environment. Many of these animal models use a sham control, where an incision into the joint is created to trigger similar trauma and healing response of the capsule as the ACL-transected joints without any direct insult to the cartilage or ACL. Sham-operated limbs do not experience the kinematic changes or changes in cartilage metabolism that ultimately result in OA as do ACL-transected limbs, offering strong evidence that trauma and the ensuing inflammatory healing response by themselves do not lead to OA [36, 38, 40, 41]. The role of the mechanical changes in the joint in initiating cartilage degeneration is best explored within the context by which cartilage adapts to its load history.

The cartilage adapts to the chronic loading that occurs during repetitive activities, such as walking. The load distribution between the knee's lateral and medial compartments is not equal during walking; typically, a greater compressive load is experienced in the medial compartment than the lateral compartment [42–44]. This imbalance in compressive load between medial and lateral compartments can be approximated by the external knee adduction moment [43, 45]. The higher the knee adduction moment, the greater the load on the medial tibial plateau compared to the load on the lateral tibial plateau (Fig. 8.2). In the healthy knee, there is a positive relationship between the knee adduction moment and the thickness of the medial femoral cartilage [46]. Specifically, the higher the proportion of the compressive load that is borne by the medial femoral compartment, the thicker the medial femoral cartilage [47]. Several MRI studies indicate that the thickest areas of cartilage occur where the tibia and femur contact at full extension, coinciding with the contact point at heel strike during walking. These thick regions of cartilage likely develop as a positive response to loading, given that the largest compressive forces occur at heel strike [43, 48, 49]. In ACL-reconstructed and uninjured limbs, knee adduction moments are a significant predictor of medial compartment contact forces [45]. Knee adduction moments also impact indicators of cartilage composition as individuals with higher knee adduction moments after ACL reconstruction have elevated T1ρ and T2 relaxation times suggestive of loss of proteoglycans and disruption of collagen matrix [50]. After ACL injury and reconstruction, the magnitudes of vertical ground reaction force and instantaneous loading rates immediately following heel strike are higher in the reconstructed limb compared to the contralateral limb [51]. However, reduced knee extension at this time point in the

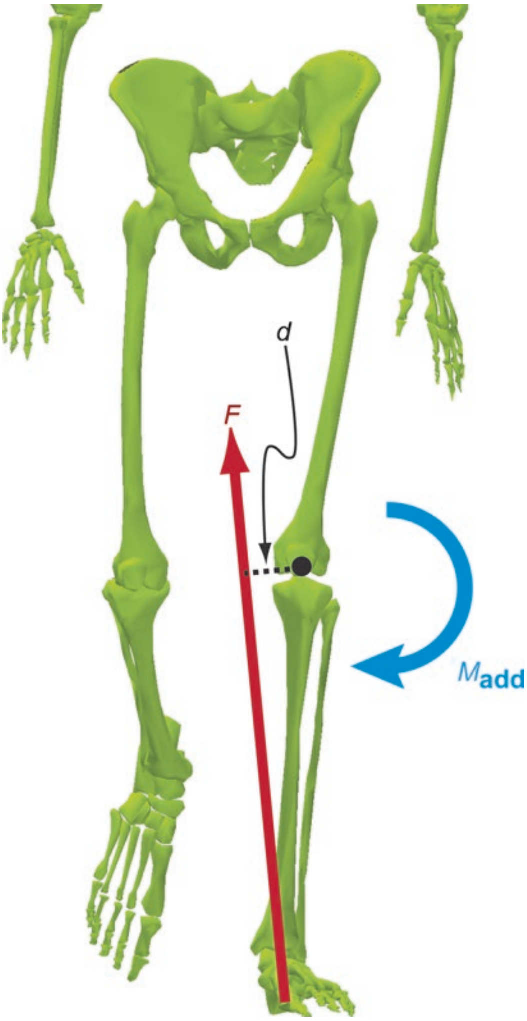

Fig. 8.2 Illustration of the knee adduction moment. The ground reaction force vector (*F*) passes medially to the knee joint center with moment arm *d*, resulting in an external knee adduction moment (M_{add}). As the moment arm of the ground reaction force increases, the load on the medial compartment increases relative to the lateral compartment

gait cycle in ACL-reconstructed knees does not correlate with magnitude of medial or lateral femoral cartilage thickness at 2 years post-reconstruction [52]. Cartilage also responds to a lack of loading. Immobilization or inactivity that limits external joint loading results in a lack of cartilage matrix stimulation and thinning of the cartilage tissue [53–55]. Lower knee flexion and adduction moments are apparent during gait and stair-climbing activities following ACL reconstruction [56, 57]. Recent work indicates that markers of reduced knee joint loading during gait are associated with greater concentrations of enzymes associated with cartilage degradation and pro-inflammatory cytokines at 6 months post-ACL reconstruction and with early knee osteoarthritis 5 years post-ACL injury and reconstruction [58–61]. In the sagittal plane, reduced knee flexion angles and lower knee flexion moments persist for years following ACL injury and reconstruction [62, 63], suggesting that further understanding of these variables with cartilage metabolism is warranted. Clearly, more study regarding joint overloading or underloading with regard to cartilage structure, composition, and metabolism will shed light into mechanisms associated with the development of knee OA in this population.

Laboratory studies support the hypothesis that cartilage responds to functional loads. On the cellular level, applied compression and shear loads to two-dimensional chondrocyte cultures and to three-dimensional agarose gels seeded with chondrocytes result in metabolic changes [64–74]. The chondrocytes proliferate in response to dynamic hydrostatic compression and create additional extracellular matrix components, such as proteoglycans and type II collagen [72]. In response to shear stresses, proteoglycan production increases, while the expression of matrix metalloproteinases declines [65, 73, 74]. Finally, an increased load causes chondrocytes to respond by changing their volume and aspect ratio [73, 75].

Cartilage tissue explants exposed to compression also demonstrate increased proteoglycan deposition [76–78]. Alterations to the cytoskeleton appear to vary according to the magnitude of compression [79], although the response to compression is not consistent across the cartilage [80] or across varying magnitudes and durations of loading. A more complex process of creation and destruction of cartilage matrix components appears to be governed by the magnitude of tissue stresses [78], proximity to chondrocytes [77], and changes in fluid flow [76], as well as the origin of the explant from the articular surface [80].

In vivo study of the entire knee joint yields similar effects to those observed at the cellular and tissue level. Immobilization of the hind limbs in rabbits [81] and dogs [82, 83] combined with unloading of the limb results in thinning of cartilage. In the canine model, loose immobilization that still allows limited cyclic loading of the joint results in less irreversible proteoglycan loss than rigidly fixed immobilization [82]. Conversely, increased joint loading leads to thicker cartilage and increased proteoglycan content, regardless of whether the loads on a joint are increased by additional exercise [83] or by the immobilization of a contralateral limb [84].

The same changes in cartilage structure in response to loads and compression may be seen at each level of scientific study, from the cellular level to an in vivo study of the entire limb in a controlled laboratory experiment. Histological evidence indicates that topographical variations in the collagen structure and the morphology of chondrocytes are based on the local loading environment. For example, in the central regions of the tibial plateau, femoral cartilage appears to have a less-organized superficial zone and more random collagen fiber orientation [85–87]. In addition, the chondrocytes are larger and rounder [86, 88, 89]. However, in the peripheral areas of the tibial plateau, such as beneath the meniscus, cartilage is more organized and well defined, and the chondrocytes are smaller and flatter [85–87, 90]. Because of collagen's role in supporting tensile loads, a more organized matrix near the peripheral areas could be attributed to the larger tensile loads in that area, an assumption that has been supported by computer models of cartilage growth [54]. These topographical observations have two consequences. First, they support the hypothesis that cartilage reacts and adapts to the local loading environment; this adaptation occurs at the level of individual chondrocytes, across the surface of cartilage, and throughout its depth. Second, the topographical evidence supports a mechanism to explain the initial breakdown of cartilage after a shift in motion of the joint and the subsequent pattern of cartilage loading. The different structures of collagen and the morphology of the chondrocytes appear conditioned to local load history and appear to demonstrate different abilities to withstand alterations of the compressive, tensile, or shear loads to which they are exposed. In the next section, a theoretical process is provided for the initiation of OA at the knee following ACL injury based on the above evidence.

Critical Points

- Studies indicate that joint trauma and the inflammatory response may initiate the development of OA, but the mechanical process propagates long-term degeneration.
- Collagen and chondrocytes demonstrate physical changes in response to local loading and vary in ability to withstand compression and loads.
- Within the knee joint, areas that routinely experience high loads are areas with thicker cartilage, whereas lack of joint loading tends to result in cartilage thinning.

8.4 Kinematic Pathway to Osteoarthritis After ACL

The kinematic and degenerative changes affecting the knee joint after ACL rupture, in conjunction with the response of cartilage to loading at the cellular and tissue level, support a mechanism of initiation of OA after ACL injury. The change in knee motion caused by ACL injury results in shifts in regions of cartilage contact, thereby increasing loads in areas not accustomed to frequent load bearing. Conversely, areas conditioned to frequent load bearing experience reduced loading. These shifts change the contact pressure distributions under static loading [91]. In the case of altered rotation, a relatively small shift in one area can lead to important changes in another depending on the location of the pivot point [92]. For example, an internal tibial rotation of 10° may not appear to change much in regard to loading on the medial side of the tibial plateau but could result in a posterior shift in contact pressure on the lateral side if the pivot point is located in the medial compartment.

Regions of functional load bearing may be seen as a map to understanding both the existence of spatial variations in cartilage morphology and mechanical properties [76, 78, 85–87, 93] and the ramifications of changes to loading on the health of the cartilage (Fig. 8.3). The central regions undergo the highest compressive loads [91, 94]. As the surfaces of the central regions are pulled downward and interstitial fluid is pushed out of the central region, the peripheral regions of the cartilage likely receive greater tensile tangential loading at their surfaces. As one would expect from the previously mentioned response of cartilage to load (see Sect. 8.3), the peripheral regions are thinner, with a better-defined superficial layer containing greater tangential collagen fiber orientation [85–87]. Conversely, the central regions show increased thickness and a less-organized superficial layer of collagen [85–87].

Following ACL injury, abnormal motion and rapid shifts in loading may create tension in the central regions, leading to the potential for fibrillation and fluid and proteoglycan loss. Overloading via increased compression in the peripheral areas leads to fiber breakdown. There is no adequate biological response to arrest this dynamic process, and the damage to cartilage cascades into increasing susceptibility to further damage, progressive cartilage breakdown, and ultimately bulk tissue failure. It is not clear whether simple compressive overloading is the predominant process during the initiation of OA or if altered loading from compression to tension in the central regions (and vice versa in the peripheral regions) predominates. However, the evidence that cartilage thinning and OA may be initiated by immobilization [54, 81, 82, 84] suggests that simple overloading may not be the primary factor. Alterations in loading most likely contribute significantly to the degradative process.

In the early stages of OA, surface changes have frequently been reported including matrix consolidation associated with loss of proteoglycans at the surface layer, as well as fibrillation [36, 72, 95, 96]. The increase of friction after fibrillation at the surface tends to increase the tangential force at the articular surface, which in turn is a potential source of fracture of the fibrils and further surface fibrillation [97, 98]. Tangential surface traction and associated shear stress within the cartilage lead to upregulation of catabolic factors, such as matrix metalloproteinase and interleukins [40, 65, 99]. The relationship between all of these factors in the wake of the initiation of increased frictional forces creates a cycle (Fig. 8.4). Increased tangential forces lead to fibrillation and catabolic activity, which in turn lead to increased friction. The cartilage becomes negatively sensitized to increased pressure loads, as friction changes cartilage-stimulating compressive stresses into cartilage-degenerating shear stresses in the tissue. When the cartilage undergoes this change in response to stimuli, OA moves from its initiation phase to its progression phase, and increased loads lead to more rapid degeneration [47, 100].

Critical Points

- The mechanism of initiation of OA is suggested by the biological response to kinematic changes.
- It is not known whether *increased* loading or *any alteration* in loading leads to cartilage damage, but studies of immobilized limbs suggest increased loading alone is not a likely explanation.
- The relationship between kinematic changes and biological response suggests that the initiation and progression of OA are a cyclical cascade of effects, as increases in tangential forces lead to greater friction, and greater friction in turn leads to further increases in tangential forces.

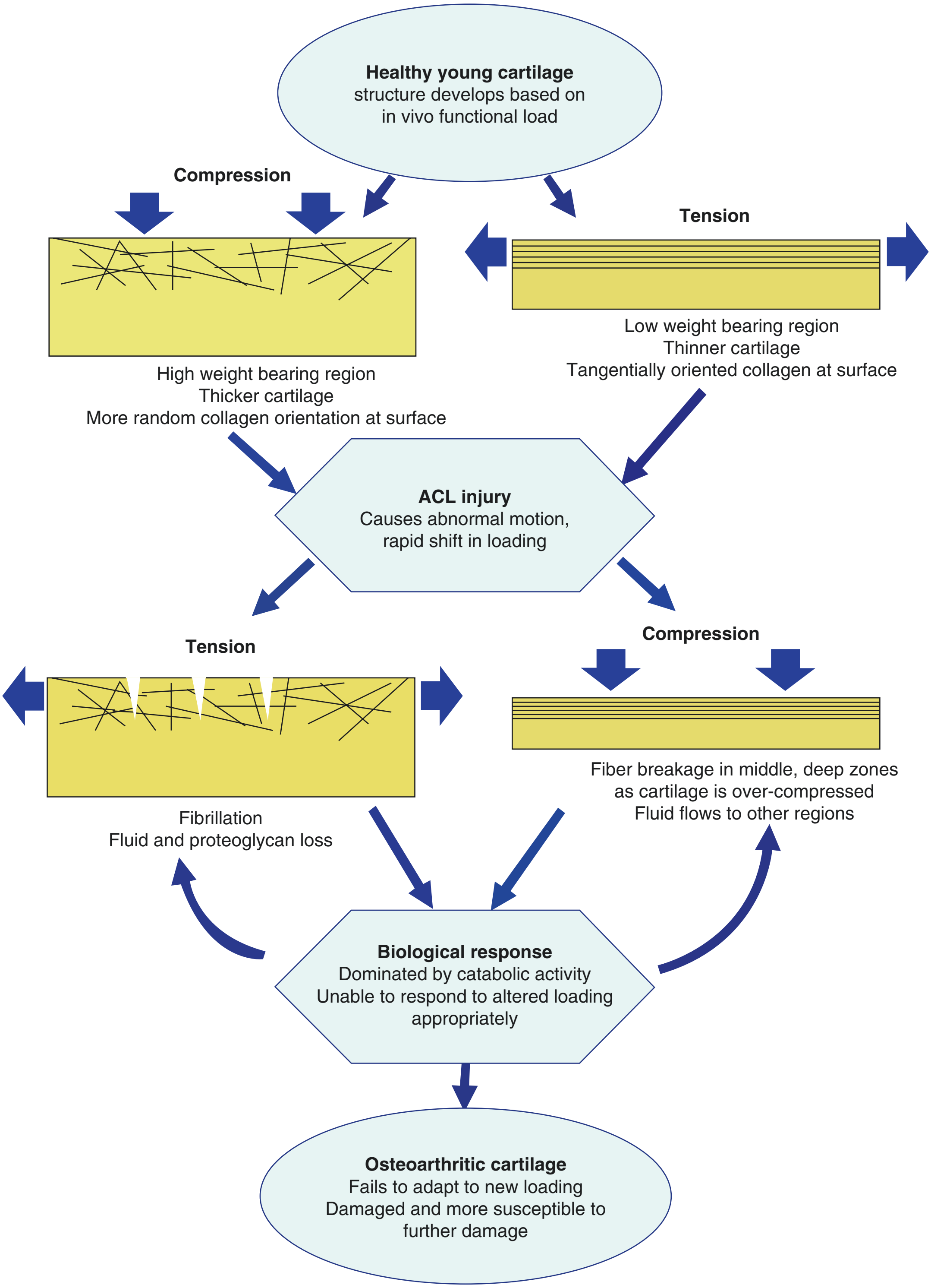

Fig. 8.3 A proposed mechanism of initiation of osteoarthritis after ACL injury. Healthy cartilage that has developed heterogeneous specialized structural morphology over a lifetime is subjected to abnormal motion and loading after ACL injury. These rapid changes result in fibrillation and other structural breakdowns as well as catabolic biological responses, initiating the pathway to osteoarthritis (Reproduced with permission from Chaudhari et al. [101])

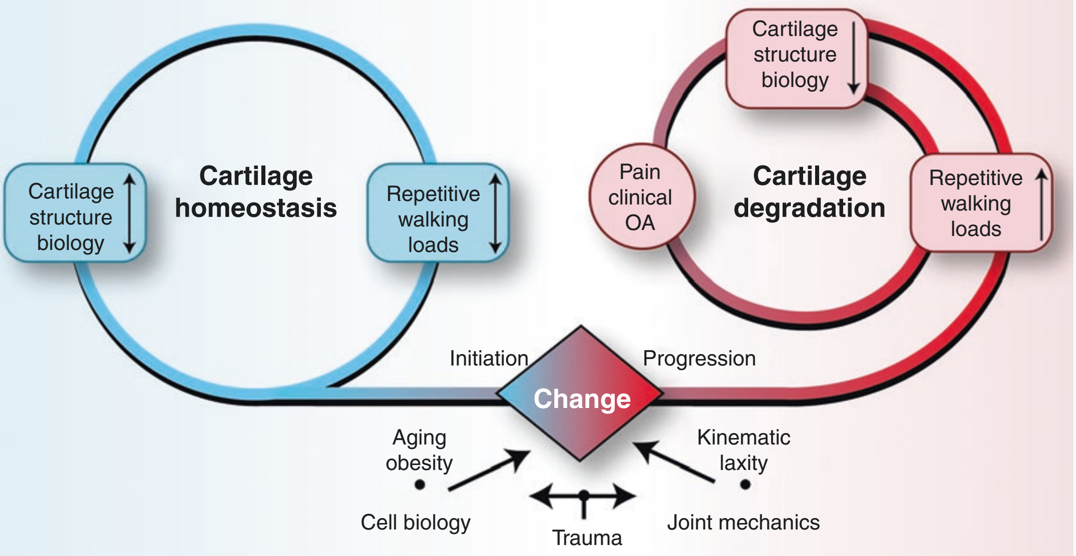

Fig. 8.4 Healthy cartilage homeostasis is maintained by the magnitude of the repetitive cyclic loads during walking, and cartilage is thicker in regions with higher loads during walking. The initiation of osteoarthritis (*OA*) is associated with a change (due to injury, increased laxity, neuromuscular changes, aging, or increased obesity) in the normal balance between the mechanics of walking and the cartilage biology or structure. Once cartilage starts to degrade, it responds negatively to load, and the rate of progression of osteoarthritis increases with loading (Reproduced with permission from Andriacchi et al. [46])

Conclusion

Clinical data strongly indicate that patients who have suffered an injury to their ACL are at higher risk for developing OA. Human motion analysis supports the observation that altered rotational positions in the ACL-deficient knee lead to changes in tibiofemoral contact during walking. In turn, these kinematic changes alter the types of loads normally experienced by cartilage in different areas of the joint, initiating a cycle of tissue degeneration in which past injury leads to altered motion, leading to degeneration of tissue, leading to continued kinematic changes and progressive OA. However, the initiation of the disease appears to be the consequence of a kinematic shift that precedes and triggers biological changes. This mechanism provides a framework for studying OA that unifies kinematic and biological investigations and should inform the development of techniques to prevent the initiation and progression of OA in the ACL-injured population.

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9

Analysis of Male and Female Athletes' Muscle Activation Patterns During Running, Cutting, and Jumping

William P. Ebben and Timothy J. Suchomel

Abstract

This chapter provides a comprehensive assessment of the biomechanics of ACL injuries and the muscle activation patterns contributing to and potentially preventing these injuries. Muscular activation differences between genders are compared during activities such as running, cutting, and jumping. Activation patterns and gender differences of muscles associated with the ankle, knee, and hip joints are described for each of these functional activities. Gender differences in dynamic neuromuscular control as a function of kinetic and kinematic factors in the sagittal, frontal, and transverse planes are discussed.

9.1 Introduction

The etiology of anterior cruciate ligament (ACL) injuries includes a variety of intrinsic and extrinsic factors [1–5]. Non-modifiable intrinsic factors for women include hormonal issues, limb alignment, intercondylar notch size, ACL ligament size, and joint laxity [1, 3, 4, 6, 7]. Evidence does not support the presence of similar intrinsic risk factors for men [8]. In addition to these intrinsic factors, there exist a variety of extrinsic factors such as the type of sport played, the environmental conditions, equipment, playing surface, and athlete strength and conditioning [2, 8]. It should be noted that previous ACL injury also increases the likelihood of re-injury of the same limb and thus is a risk factor as well [9].

Modifiable intrinsic risk factors include athlete conditioning and the timing and magnitude of the patterns of neuromuscular recruitment in order to optimize the ability of the muscle and connective tissue to limit stress on the knee joint and to potentially provide protection [1, 3–7, 10]. Gender differences in neuromuscular recruitment and muscle activation patterns during athletic movements may explain, in part, why women are 2–8 times more likely than men to rupture the ACL [6, 7, 10]. Thus, priority should be given to understanding the role of timing and magnitude of muscle activation during movements which are most likely produce injury, including dynamic athletic tasks such as running, cutting, and jumping. Of these risk factors, athlete strength and conditioning programming are an area where sports medicine and strength and conditioning professionals may be most able to intervene to reduce ACL injuries [1, 5, 6].

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Multimodal ACL injury prevention programs have been recommended and evaluated, including education and feedback about body mechanics during running, cutting, and jumping and landing, proprioceptive and balance training, and other neuromuscular modes of training such as resistance and plyometric training [1, 4, 5]. Additionally, laboratory and field-based screening methods have been increasingly researched, with some evidence showing that qualitative assessment of landing mechanics has predictive validity for identifying those at greatest risk of injury [11].

There exists a complex interaction between non-modifiable and modifiable risk factors. Ultimately, for the prevention of ACL injuries, neuromuscular training is one of the limited numbers of potentially modifiable options available. Programs designed to prevent ACL injuries often focus on training the neuromuscular system in order to improve the hamstring-to-quadriceps (H:Q) ratio, hip abductor strength, lower limb biomechanics such as abduction/adduction moments, hip alignment, trunk position, dynamic balance, and fatigue resistance [1, 5, 8, 12, 13]. For those who have previously had ACL injuries, insufficient landing force attenuation, which is mediated via neuromuscular processes, is implicated as the cause of re-injury [9]. Furthermore, hamstring fatigue is associated with mechanical loss of knee joint stability, resulting in reduced electromyography (EMG) amplitude and increased reflex latency which corresponds to increased anterior translation of the tibia and ACL strain when the hamstrings were fatigued [13]. Some evidence shows that neuromuscular training reduces the risk of ACL injury, potentially through reduced fatigue [12, 14]. In order to maximize the potential for neuromuscular training to reduce ACL injuries, a comprehensive assessment of the biomechanics of these injuries and the muscle activation patterns contributing to and potentially preventing these injuries is required. Since males suffer from much lower rates of ACL injury compared to females, it is instructive to compare muscular activation differences between genders.

Critical Points

- There are both modifiable and non-modifiable risk factors.
- Gender differences in muscle activation patterns are present during running, jumping and landing, and cutting.
- Gender differences in muscle activation are likely to be part of the reason why women have 2–8 times higher rate of ACL injuries.
- Neuromuscular recruitment patterns and muscle activation can be changed through training, which may decrease the likelihood of ACL injuries.

9.2 Experimental Approach to Understanding Muscle Activation Patterns During Running, Cutting, and Jumping

Gender differences in muscle activation have been evaluated for a variety of muscle groups during a number of dynamic movements. Movements which have been most commonly assessed include running, cutting, and jumping, with much of the focus on jump landings. Muscle activation has been studied during these movements because they have been implicated as part of the etiology of ACL injuries [6, 7, 12].

Surface EMG has been commonly used and found to be reliable for assessing muscle activation and timing during running [15], cutting maneuvers [16], and jump landings [16]. EMG assesses the magnitude of muscle activation before and after foot contact during running, cutting, and jumping. In addition to evaluating the magnitude of muscle activation, the timing of muscle activation has been studied before and after foot contact, since both the magnitude and timing of activation are believed to be important for postural control, knee joint stability, and ACL injury prevention for females [1, 4–7, 10, 12, 13, 17, 18] and athletes with previous ACL injuries [9] but not in male athletes [8].

A variety of muscles have been studied including the gastrocnemius, tibialis anterior, gluteus medius, and the lateral hamstrings and medial hamstrings, which include the biceps femoris and combination of semitendinosus and semimembranosus, respectively. Studies have also examined the role of trunk posture and its potential to influence knee mechanics. Some sources refer to the quadriceps muscles group, while other studies have specifically examined the rectus femoris, vastus lateralis, and vastus medialis.

Movements have been examined in all three cardinal planes of motion and across a variety of joints. For the purpose of this chapter, the muscles that cross the articulation of the acetabulum and femur, which is also known as the acetabulofemoral joint, will be referred to as the "hip joint" for simplicity and due to the fact that this joint is often described as the hip joint in the literature. Similarly, the articulation of the femur and tibia which is commonly labeled as the tibiofemoral joint will be referred to as the "knee joint." Finally, the articulation of the distal tibia and lateral malleolus of the fibula and the talus, commonly known as the talocrural joint, will be referred to as the "ankle joint." The movements associated with each of these joints require some clarification as well. Movements are sometimes described in reference to the joint, such as "knee joint internal rotation," while others describe the movement of a joint segment or the bone, such as "tibial internal rotation." To the degree possible, these differences in descriptions will be clarified, and the joint movement will be described based on the motion associated with each joint segment, in order to present the greatest degree of precision.

While the focus of this chapter is on muscle activation during running, cutting, and jumping, the segment and joint biomechanics of these types of movements will be considered as well. Biomechanical factors such as the kinetics and kinematics of these movements share a complex interaction with muscle activation patterns. Often, the kinetics and kinematics of running, cutting, and jumping are the determinants of muscular activation, while at the same time the nature of the muscle activations influences these biomechanical factors. Some of these biomechanical factors increase the risk of ACL injuries. In many cases, training the optimal muscle activation patterns may be the best option available to clinicians to remediate these undesirable biomechanical issues. Consequently, the subsequent section outlines a variety of biomechanical responses in each of the cardinal planes of motions associated with running, cutting, and jumping. This chapter then proceeds to specifically examine muscle activation of during running, cutting, and jumping.

Finally, while most studies examined these issues with young adults, some researchers used trained or untrained subjects or adolescents. As a result, gender differences in muscle activation and timing can be best understood for these types of subjects. Collectively, these studies provide convoluted picture at times, while in other cases, a clear understanding is presented of the gender differences in muscle activation during dynamic movements. Therefore, the focus of this chapter is to review, characterize, and evaluate the gender differences in muscles activation during running, cutting, and jumping and consider the implications of these data for ACL injury prevention.

Critical Points

- A variety of dynamic movements such as running, cutting, and jumping and landing demonstrate gender differences in muscle activation.
- Muscle activation is typically assessed with EMG.
- Studies examining gender differences in muscle activation often assess the magnitude as well as the timing of activation.
- Biomechanical factors such as the planes of motion of movement and the forces associated with running, cutting, jumping and landing influence muscle activation.
- Research has been conducted most often with fit young adults and occasionally with adolescents and young adult athletes.

9.3 Biomechanics of ACL Injuries

Gender differences in dynamic neuromuscular control are partially a function of kinetic and kinematic factors in the sagittal, frontal, and transverse planes. In other words, the acute movements and forces that predispose a person to injury are multiplanar and complex. These movements and forces that affect the ACL are most likely to occur shortly after foot contact during athletic movements [18]. Research shows that during the initial 40% of the stance phase of cutting movements, women compared to men had less flexible coordination movement patterns, as evidenced by greater variability in inter-limb segment and joint coupling, as assessed with three-dimensional kinematics [19]. These differences in segment and joint coupling may predispose women to ACL injuries, since they may be less able to manage the numerous and variable limb and joint loads present during sports [19]. During the initial stance phase, peak ACL length has been shown to be the greatest, corresponding to approximately 50 ms after foot contact and then decreases with knee flexion during landing [18]. As a result of the complex multiplanar biomechanics during foot contact, a variety of muscles may contribute to and/or resist potentially undesirable kinematic and kinetic reactions during this critical period after foot contact during dynamic activities such as running, cutting, and jumping.

9.3.1 Sagittal Plane Mechanics

Some researchers found no or limited gender differences in sagittal plane biomechanical factors, such as knee flexion angle during unanticipated cutting after a jump stop [20]. On the other hand, the majority of work assessing this issue found differences, such as women landing with less knee and hip flexion compared with men [1, 3–5, 21]. Investigators have reported that the quadriceps contribution to anterior shear of the tibia is thought to be maximal when the knee is flexed <30° [7] and the length of the ACL decreases with increased knee flexion angle [18]. This belief is supported by research showing the greatest ACL loading occurs at 22.0° of flexion for men and 24.9° for women [10]. Figures 9.1 and 9.2 show a theoretical depiction of knee joint forces during a jump landing with limited knee flexion and greater knee flexion, respectively. Unfortunately, during some dynamic tasks such as side-step cutting, women produce less hip and knee flexion compared to men [22], which likely increases the quadriceps role in ACL loading in women. Muscles crossing the knee and ankle may play an important role in dynamic stabiliza-

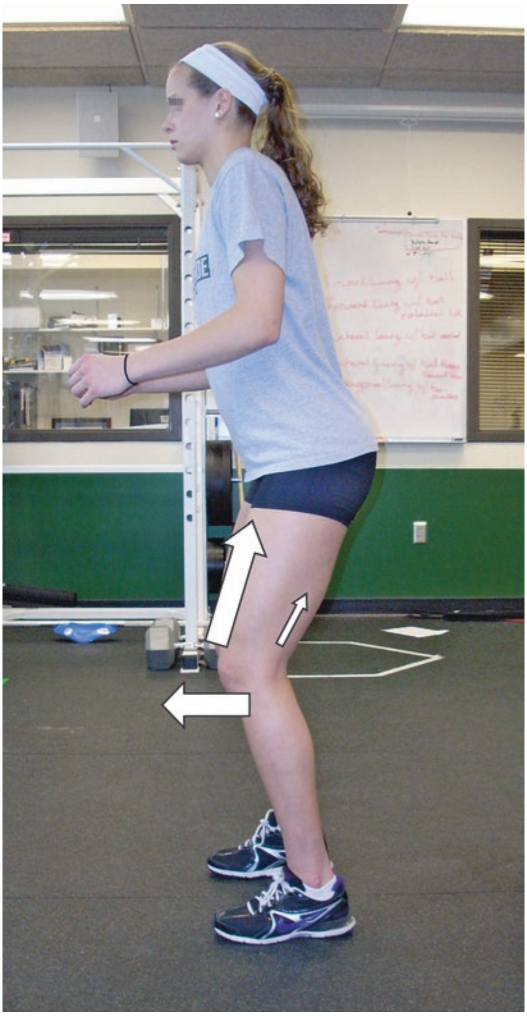

Fig. 9.1 Sagittal plane view of landing with vectors representing a large quadriceps force, limited hamstring force, and anterior tibial translation

tion of the ACL in the sagittal plane and may help prevent ACL injury [7]. Thus, the muscle activation patterns of the hamstrings as well as the gastrocnemius are important for knee joint stabilization, particularly during fatigued conditions [7]. However, some evidence suggests that muscle activation during sagittal plane movements is insufficient to rupture the ACL during some types of cutting [23]. Dynamic musculoskeletal modeling of subjects during side-step cutting reveals that anterior drawer forces are not high enough to rupture the ACL [23], with quadriceps muscles producing only approximately half of the anterior tibial shear force required to induce ACL rupture [17].

Fig. 9.2 Sagittal plane view of a desirable landing position

9.3.2 Frontal Plane Mechanics

While the importance of sagittal plane mechanics in the explanation of ACL injuries is equivocal, it is clear that frontal plane mechanics are problematic. Hewett et al. [7] reviewed the role of increased knee valgus in increasing ACL injury. During knee valgus, medial femoral condyle lift-off and lateral femoral condyle compression occur, which in turn loads the ACL [7]. More specifically, the mechanics of injury during knee valgus seems to be ACL impingement against the lateral wall of the intercondylar notch [24], which occurs with both frontal plane knee valgus as well as transverse plane external tibial rotation. Thus, ACL injury mechanics are likely to be multiplanar. However, frontal plane valgus loads alone have been shown to be high enough to rupture the ACL. These levels of loads occur more commonly with women than men [23].

Compared to males, females have greater hip adduction [1, 25], higher knee valgus angles [1, 3, 4], and greater variability in knee valgus [22]. Gender differences are characterized by women having greater ankle eversion [20, 26] and hip adduction [22, 25, 26], each of which contributes to the valgus knee condition [26]. Additionally, women demonstrate greater frontal plane torso angle, characterized by lateral pelvic tilt and lateral spinal flexion that may increase knee adduction moments [27]. Additionally, females demonstrate higher frontal plane angular velocity at the knee, indicating they collapse into valgus more rapidly than males [26]. Concerns such as these apply to adolescent females who demonstrated greater knee valgus angles at initial contact compared to adolescent males [20]. Even among older and more highly trained subjects such as college

Fig. 9.3 Frontal plane view of valgus knee position

Fig. 9.4 Frontal plane view of varus knee position

basketball players, women have greater knee valgus than men during side-step cutting movement [28]. In addition to frontal plane biomechanics at the knee, females demonstrate more ankle eversion and less inversion during unanticipated cutting after a jump stop [20], along with frontal plane differences represented by foot pronation angles during side-step cutting [22]. Figures 9.3 and 9.4 show a theoretical model of lower extremity forces and the role of muscle activation in the frontal plane valgus and varus conditions, respectively. Collectively, these data suggest that frontal plane mechanics may have an important role in the etiology and prevention of ACL injuries.

9.3.3 Transverse Plane Biomechanics

Similar to frontal plane biomechanics, the movements and forces in the transverse plane are also clearly implicated as part of the mechanism of ACL injuries. Sources suggest that increased internal hip rotation may potentiate ACL strain, noting that women have increased internal hip

Fig. 9.5 Transverse plane view of a relatively neutral tibia (knee)

rotation compared to men during foot contact [1, 7], including during the performance of cutting maneuvers [29]. Other studies show women compared to men had less hip and knee internal rotation during side-step cutting [22]. In this case, knee internal rotation refers to the internal rotation of the proximal femur on the fixed distal tibia, which has been characterized by others as knee external rotation [30]. Gender differences in knee rotation have been described as risk factors for injury, with females demonstrating less internal rotation and greater external rotation torque during running [25]. Other evidence shows that noncontact ACL injuries occur with, or may be exacerbated by, both internal [31] and external tibial rotation [24]. External tibial rotation, in particular, is a concern due to ACL impingement against the lateral wall of the intercondylar notch [24]. In fact, women have an externally rotated neutral resting position of the tibia compared to men, as well as higher laxity, lower stiffness, and higher energy loss in external tibial rotation [24]. While the role of the muscle in preventing this rotation is not clear, some sources suggest that the gastrocnemius is activated faster than the hamstrings or quadriceps in response to a rotation perturbation [7]. As a result, the potential role of the gastrocnemius in injury prevention deserves consideration [7]. These data show that that hip and tibial rotation are likely to be important factors in ACL injuries, with knee external rotation representing the issue of greatest concern. Figures 9.5 and 9.6 show a neutral and an internally rotated tibia, respectively. Figure 9.7 shows an externally rotated tibia, which is representative of the frontal plane condition that contributes the most to knee injuries.

Fig. 9.6 Transverse plane view of an internally rotated tibia (knee)

Fig. 9.7 Transverse plane view of an externally rotated tibia (knee)

9.3.4 Summary

Based on these studies assessing the kinetic and kinematic responses to running, cutting, and jumping, it appears that the role of sagittal and transverse plane mechanics is equivocal. The mechanics of concern in the sagittal plane are clear, but what is less certain is if these issues alone, characterized by quadriceps-induced anterior translation of the tibia, are enough to rupture the ACL. In the transverse plane, femoral internal rotation (and thus tibia external rotation) as well as tibial internal rotation may each be part of the biomechanics of ACL injuries, though most of the evidence implicates external rotation of the tibia as the issue of greatest concern. However, the role of frontal plane biomechanics seems more certain. Knee valgus (potentially induced in part by eversion of the foot and adduction of the femur), lateral pelvic tilt and lateral flexion of the torso, dominance of the lateral compared with the medial aspects of the hamstring and quadriceps during noncontact conditions, and the addition of lateral exogenous forces during contact conditions, increase ACL injury risk. Athletes need to develop muscle activation strategies to resist these undesirable movements in all planes of motion since it is likely that ACL injuries are a function of the biomechanical factors in all cardinal planes of movements [32].

Critical Points

- Movements in each plane of motion are caused by external forces as well as muscle activation.
- Muscle activation may produce undesirable movements in each plane of motion, potentially compromising the ACL.
- Lower extremity movements in the sagittal and transverse planes may be part of the etiology of ACL injuries.
- Frontal plane biomechanics including ankle eversion, femur adduction, knee valgus, and frontal plane torso angle, characterized by lateral pelvic tilt and lateral spinal flexion, may increase knee adduction moments.
- Frontal plane biomechanical issues of concern include the dominance of the lateral knee flexors and extensors which contribute to knee valgus.
- Stress to the ACL is likely to include movements which simultaneously occur in all planes of motion.
- Gender differences in these muscle activations are likely to either add to or prevent undesirable movements and thus influence ACL stress.
- Training should focus on developing muscle activation patterns in an attempt to resist these undesirable movements.

9.4 Muscle Activation Patterns During Running

A number of studies have assessed muscle activation during gait, including running in barefoot and shod conditions [25, 33, 34], on treadmills [35–37], over ground [25, 33, 38, 39], on grass compared to tartan surfaces [34], and during various running speeds [25, 37–39]. Some of these studies were conducted with the expressed purpose of assessing gender differences [25, 33, 36, 37, 40, 41], whereas others used both male and female subjects in the analysis without identifying gender differences as part of the purpose of the study [38, 39]. Some researchers examined muscle activation differences of subjects who were rehabilitated or underwent ACL reconstruction [42]. Of the studies that compared the muscle activation responses between men and women, some found a number of gender differences in activation of muscles that cross the ankle, knee, and hip joints, although the implications for ACL injury risk or neuromuscular protection remain equivocal.

9.4.1 Activation of Muscles Commonly Associated with the Ankle Joint

Many studies designed to assess gender differences in muscle activation during running have examined muscles that cross the ankle joint. These studies have focused on muscles such as the tibialis anterior [33], peroneus (fibularis) longus [34, 40], soleus [37], and the medial and lateral gastrocnemius [33, 38, 39]. In some cases, the results of these studies show that there are no gender differences in muscle activity during the swing phase of running or at any period prior to ground contact. For example, research failed to find any gender differences in activation of muscles such as the medial gastrocnemius, lateral gastrocnemius, or soleus prior to foot contact during treadmill running [37] or for activation of the lateral gastrocnemius and the tibialis anterior while sprinting over ground [39]. On the other hand, some evidence suggests that women, compared to men, have more activation of the peroneus longus prior to foot contact during treadmill running [40] and less preactivation of the tibialis anterior [33].

After foot contact is made during running, gender differences in muscle activation are more pronounced. Studies show that there are gender differences in activation of the tibialis anterior, peroneus longus, and gastrocnemius. One investigation reported that after foot contact, low-frequency aspects of EMG of the tibialis anterior were higher for females than males [33]. The tibialis anterior short-time mean frequency EMG raised 20 ms earlier for women compared to men, potentially due to a shorter stance phase [33]. Finally, women, compared to men, had more tibialis anterior activation during the toe-off portion of the stance phase [33]. Activation of the tibialis anterior in the early and late stance phase of running is typical for uninjured subjects compared to those who had undergone ACL rehabilitation or surgical repair [42] and thus may be construed as the normal condition. In addition to the activation of the tibialis anterior, gender variability in peroneus longus activation was reported in a study examining running in barefoot and shod conditions, although the written description does not make clear the specific details of these differences [34]. However, others found clearer gender differences in the timing and magnitude of peroneus longus activation [40]. For example, the onset of activation of peroneus longus was earlier, and the timing of maximum activation was longer in healthy women compared to men during treadmill running. However, women demonstrated comparatively less muscle activation of the peroneus longus during foot contact and at the point of push-off late in the foot contact phase [40].

While much of the research focus has been on the gender differences in peroneus longus and tibialis anterior activation, researchers have also assessed differences in gastrocnemius activation. Some evidence suggests that the magnitude of gender differences is determined by running speed, such that women increased gastrocnemius activation more than men as sprinting speeds increase [38]. The specific characteristics of these differences in muscle activation have also been assessed by examining the frequency aspects of EMG. Results reveal differences in the activation of the medial head of the gastrocnemius, characterized by women demonstrating larger low-frequency aspects of muscle activity following heel strike but lower high-frequency aspects 50 ms after heel strike [33].

9.4.2 Activation of Muscles Commonly Associated with the Knee Joint

Gender differences in the activation of the muscles that cross the knee joint have also been studied in order to quantify these findings during running. In all cases, researchers have studied muscles typically referred to as part of the "hamstring" group, including the biceps femoris, semitendinosus, and semimembranosus [33, 38, 39, 43], or the "quadriceps" group, including the rectus femoris, vastus medialis, and lateralis [33, 34, 36, 38, 39].

Some evidence suggests that there are no gender differences in pre-foot contact muscle activity for specific hamstring or quadriceps muscles such as the biceps femoris, rectus femoris, or vastus lateralis [39]. Nonetheless, other researchers have reported gender differences. For example, women have higher precontact low-frequency hamstring activation during running [33]. Additionally, after foot contact, women have less hamstring activity during the stance phase of running [33]. The magnitude of hamstring activation that occurs during gait may be influenced by training. After 3–4 weeks of ten sessions of perturbation-enhanced training, agility drills, and lower extremity resistance training, women demonstrated earlier activation of their medial and lateral hamstrings than men during foot stance while walking [43]. After training, female subjects had higher medial hamstring and lateral hamstring activity at midstance. Thus, training was able to reduce the quadriceps dominance and increase hamstring activation of women during walking [43], which raises the possibility that training may be able to alter the neuromuscular activation patterns during running as well.

In addition to the hamstrings, muscles of the quadriceps group show gender differences in activation during running. These differences include gender-specific responses in the timing and magnitude of activation of these muscles. For example, women produced less rectus femoris activation than men at 60 ms into the stance phase [33]. It is interesting to note that 60 ms into the stance phase is likely to be after the landing breaking phase and at the approximate transition to the push-off phase of running [38]. Compared to men, women also had later onset and earlier decrease in vastus medialis activity [33]. Gender differences in vastus medialis activation appear to be manifested during both barefoot and shod conditions [34]. Studies show that in addition to gender differences in vastus medialis activation, gender-specific responses exist with respect to the vastus lateralis. Women increase their vastus lateralis activity more than men in response to increased running speed over ground [38] and on treadmills [36]. It is believed that this difference in vastus lateralis activation with increased treadmill running speed is possibly due to greater nonsagittal motion [36]. Similarly, women increased their vastus lateralis activation more than men with increasing sprinting speed while running over ground [38]. In addition to gender-specific responses to acute variables such as sprinting speed, differences are also affected by training. For example, peak vastus lateralis activation values were higher at midstance for women than men in one study before training [43]. However, after training women produced lower peak vastus lateralis values that were similar to the values demonstrated by men during some forms of gait such as walking.

9.4.3 Activation of Muscles Commonly Associated with the Hip Joint

Gender differences are present with respect to the activation of muscles that cross the hip joint during running. While there are no gender differences in pre-foot contact activity for gluteus maximus [38, 39], overall muscle activation during running has been shown to be approximately 53% higher for women than men [25]. As intensity increases, such as during increased speeds of treadmill running, women demonstrate a greater increase in gluteus maximus and medius muscle activations than men [36]. This response is thought to be due to greater nonsagittal plane motion of women [36], typified by greater hip adduction and knee abduction angles during the stance phase of running [25].

9.4.4 Summary

Gender differences in muscle activation during running have been found for a variety of muscle groups. Compared to men, women have greater activation of the peroneus longus [40] but less activation of the tibialis anterior [33] prior to foot contact during treadmill and overground running, respectively. The tibialis anterior short-time mean frequency EMG raised 20 ms earlier for women compared to men, potentially due to a shorter stance phase [33]. Additionally, after foot contact, women have less hamstring activity during the stance phase of running [33]. Some evidence suggests that there are gender differences in fatigue resistance during running [25, 44] even though women increase muscle activation to a greater degree, compared to men, when sprinting speeds increase. This finding is true for the gastrocnemius, gluteus maximus, gluteus medius, and vastus lateralis activity which increase more for women than men in response to increased running speed over ground [38] and on treadmills [36]. Muscle activation has been found to be higher for women, regardless of running intensity [25]. Some gender differences in muscle activation are thought to be related to body weight and connective tissue, dynamic segment alignment, as well as gender-specific movement behavior [34] that is potentially due to greater frontal and transverse plane movement [25, 36]. Despite potential gender differences in movement patterns and muscle activation, possible differences in running mechanics, and concerns about increased muscle activation resulting in premature fatigue, it is not known if these issues are predisposing factors for ACL injuries. In fact, most of the studies on gender difference in muscle activation during running seem to have been conducted for the purpose of understanding sprinting or endurance running performance as opposed to the assessing the mechanism or likelihood of ACL injury.

Critical Points

- Women increase muscle activation to a greater degree, compared to men, with increased sprinting speeds.
- Women compared to men had less hamstring but greater gluteus maximum activity during the stance phase of running.
- Some gender differences in muscle activation may be potentially due to or cause greater frontal and transverse plane movement for women.
- Compared to jump landings and cutting, ACL injuries associated with running are not established in the literature.

9.5 Muscle Activation Patterns During Cutting

Gender differences in muscle activation have been examined during cutting movements including side or side-step cutting [29, 45–51], sprint and 45° cutting [2, 27, 50], jump landing and 45° cutting [52], crosscutting [48, 49], and pivoting [53]. In some studies, the cutting maneuvers were anticipated by the subjects, indicating they were aware of the direction of the cut before executing it, whereas other studies incorporated unanticipated cutting where subjects received a visual stimulus that required a quick reaction [27, 35, 47–49]. Many of these studies assessed the timing and magnitude of muscle activation prior to and after foot contact, since both of these variables are thought to be important for knee joint stability and ACL injury prevention [7, 47]. Collectively, these studies provide a background for understanding the gender differences in activation of muscles crossing the ankle, knee, and hip during cutting movements.

9.5.1 Activation of Muscles Commonly Associated with the Ankle Joint

Compared to men, women have greater lateral and medial gastrocnemius activity prior to ground contact and during the early stance phase of the side cut [49]. Furthermore, women have higher gastrocnemius activity [48], a medial-to-lateral gastrocnemius imbalance during unanticipated side cut [48], and higher lateral gastrocnemius activity during unanticipated crosscutting [48]. Gender differences in gastrocnemius activation are present for younger subjects as well. Adolescent females demonstrate more lateral gastrocnemius activity during precontact and the early stance phase of the crosscut than adolescent males [49]. Thus, there are clear gender differences in activation of muscles crossing the ankle joint.

9.5.2 Activation of Muscles Commonly Associated with the Knee Joint

While some evidence suggests that there are no gender differences in quadriceps muscle activation [29], lateral hamstring or medial hamstring activation [51] during side cutting [51] or biceps femoris activation during 45° cutting [52], a number of studies demonstrated differences in the timing and magnitude of activation of muscles that cross the knee joint during cutting.

Compared to men, women have greater rectus femoris activity [52] and longer rectus femoris and vastus lateralis activation after foot contact [2] and during the sprint and 45° cut [2]. Women also demonstrate an earlier and more rapid rise in rectus femoris activity prior to foot contact during crosscutting [49].

Gender differences have also been found in the analysis of the magnitude of muscle activation during cutting. Women produce less hamstring activity prior to foot contact during side cutting [29] and lower H:Q ratios [46]. Gender differences in muscle activation have also been found after foot contact including lower medial hamstring activation during the side cut, lower lateral hamstring activation during the crosscut [48], and less medial and lateral hamstring activation during the sprint to 45° cut [2]. This finding was true for adolescents [49], collegiate subjects [2], and athletes [46, 48].

In addition to lower levels of hamstring activation, women typically produce greater quadriceps activation during cutting compared to men. For example, in the first 20% of the foot contact phase of cutting, women produce more total quadriceps activation [51]. Adolescent females have shown greater rectus femoris activation early in stance [49]. Women have a longer rectus femoris and vastus medialis burst after foot contact [2] and greater vastus medialis, vastus lateralis, and rectus femoris activity throughout the stance phase [48, 49]. Additionally, compared to men, women have greater vastus lateralis and H:Q ratios during the precontact and postcontact phases of side-step cutting [46]. These gender differences were found for subjects ranging from adolescents [49] to similarly trained Division I collegiate soccer athletes [46].

9.5.3 Activation of Muscles Commonly Associated with the Hip Joint

Although numerous researchers have investigated muscle activation during cutting, activation of muscles that cross the hip joint such as the gluteus maximus and gluteus medius was not analyzed [2, 29, 35, 48, 49, 51]. As a result, little evidence exists either for the presence or absence of gender differences of these muscles. One study revealed that women demonstrated greater activation of their gluteus medius in the precontact phase of side-step cutting [46], whereas no difference in gluteus maximus activation was found during the performance of a 45° cut [52].

9.5.4 Summary

Compared to males, females have greater lateral and medial gastrocnemius activity prior to ground contact [49], higher gastrocnemius activity [48], and a medial-to-lateral gastrocnemius imbalance [48], regardless of the age of subjects. This laterality may be due to the transverse plane demands of the cut and may also be evidence of lateral dominance. Perhaps the most salient gender differences in muscle activation can be seen in muscles crossing the knee joint when assessed during a variety of cutting movements. The differences are typified by quadriceps muscle dominance, hamstring deficiency, and low H:Q ratios. For women, medial hamstring and hip external rotator training are believed to be particularly important to offset external rotation torque at the knee and internal rotation at the hip during cutting, respectively, [45]. Knee abduction toque is present during cutting and may be increased by proximal kinetic chain events such as increased anterior torso angle [27]. Finally, while some evidence suggests there are no gender differences in gluteus maximus activity between men and women [52], muscles such as the gluteus medius and gluteus maximus are surprisingly understudied, and the role of these muscles and their potential gender differences during cutting are not well understood.

Critical Points

- Gender differences in muscle activation of a variety of types of cutting movements have been assessed.
- Research shows that compared to men, women have greater gastrocnemius activation and are lateral gastrocnemius dominant.
- Women demonstrate earlier and longer quadriceps muscle activation upon foot contact.
- Women produce greater quadriceps activation and less hamstring activation during the pre- and post-foot contact phases of cutting.
- Muscles that cross the hip joint are surprisingly understudied. Some evidence shows that women activate the gluteus medius more than men in the pre-foot contact phase of cutting.
- Training to produce higher H:Q and medial-to-lateral gastrocnemius activation ratios may create more favorable knee kinematics during cutting.

9.6 Muscle Activation Patterns During Jumping and Landing

Numerous studies have evaluated muscle activation during the pre- and post-foot contact phase of jump landings to determine gender differences and the etiology of ACL injuries. Jump-landing conditions that have been studied include bilateral drop-jump landings from 15 cm [54], 20 cm [55], 24 cm [56], 30 cm [21, 54, 57], 30.5 cm [58], 32 cm [59], 40 cm [55, 60], 45 cm [54], to 45.8 cm [58], 52-cm bilateral landings after a fatigue stimulus [61], and drop-jump landings normalized to subject jump height [2]. Others have studied single-leg drop jumps from a 60-cm box [62], 100-cm forward jumps [62], 100-cm single forward hops [63–65], vertical stop jumps [66], and jumping at 50% of maximum vertical jump capability [67]. Many of these types of jump landings have been implicated as part of the etiology of ACL injuries [7]. Collectively, these studies provide a background for understanding the gender differences in activation of muscles crossing the ankle, knee, and hip during jumping and landing.

9.6.1 Activation of Muscles Commonly Associated with the Ankle Joint

Few authors have investigated the activation of muscles associated with the ankle during jumping and landing. One study found no significant gender difference in medial gastrocnemius activation during single-leg or bilateral landings from 40-cm depth jumps [60] or for the gastrocnemius during 30-cm depth jumps [21].

9.6.2 Activation of Muscles Commonly Associated with the Knee Joint

The timing and magnitude of the quadriceps and hamstring muscles have been studied by investigators seeking to determine if gender-related differences exist during a variety of jump landings. One study showed no differences in the onset of the burst of any of the hamstring muscles prior to foot contact [2]. Additionally, there were no differences in activation duration after foot contact for any of the hamstring or quadriceps muscles studied [2].

In addition to a lack of gender differences in the timing of muscle activation, some studies were unable to find differences in the magnitude of quadriceps muscle group activation during jump landings. For example, there was no significant gender difference in vastus medialis EMG when jumping at 50% of the subject's ability [67], during 30-cm depth jumps [21], or in rectus femoris activity during single-leg and bilateral conditions during 40-cm drop jumps [31, 60]. Similarly, no gender differences in vastus medialis, vastus lateralis, or rectus femoris activation were found in the precontact or postcontact phase of drop-jump landings from heights that were equal to each subject's maximal countermovement jump height [2].

Some studies have also not reported gender-related differences in the magnitude of hamstrings activation during jump landings. For example, no differences in activation of the lateral and medial hamstrings were found during the precontact phase [2] or postcontact phase in several investigations [31, 60, 67]. It is possible that fatigue may impair hamstrings function, although no gender differences during jump landing were found after fatiguing protocols [61]. Finally, there were no gender differences in H:Q activation ratio during 24-cm drop jumps [56], in single-leg conditions of the drop jump from 30 cm, for adolescent non-athletes, or during drop-jump landings from 32 cm in adolescent athletes [59]. Regardless of the type of jump studied, gender differences in H:Q activation ratio were not found in a variety of studies including those that assessed jumping at 50% of subject capability [67], during 24-cm drop jumps [56], 32-cm drop jumps [59], during single- or two-leg landings from 40 cm [60], and drop jumps normalized to jumping ability [2], or while in fatigued states [61].

Other studies have reported gender differences in the timing of muscle activation during jump landings. During the precontact phase, women were found to activate their vastus lateralis [2, 61] and vastus medialis [2] earlier and lateral hamstrings later than men [61]. Untrained adolescents activated their rectus femoris later in the precontact phase of jump landings than athletic boys and girls and their vastus medialis oblique later in the precontact phase than athletic girls [59].

In addition to the existence of some gender differences in the timing of muscle activation during jump landings, evidence demonstrates the magnitude of muscle activation may also differ. For example, women have greater rectus femoris activation prior to contact [31, 58] and 12% more activation than men for the collective average of the quadriceps muscle (vastus lateralis, vastus medialis, and rectus femoris) activation after contact during stop-jump landings [66].

Gender differences in hamstring activation during jump landings have also been found. Women demonstrate more hamstring activation before landing [66] but less lateral hamstring activation [2] or trending toward less [66] hamstring activation after foot contact during landing from jumps. In some cases, such as dropping from progressively higher drop-jump heights, the post-foot contact hamstring and quadriceps activity is higher. Thus, hamstring activity increases with greater drop jump height in some studies [54] but not in others [55]. However, with increasing jump height, the activation of the quadriceps group is consistently higher, without a similar increase in the activation of hamstring group [54, 55].

Some evidence suggests that not only are there gender differences in hamstring and quadriceps activation levels and H:Q ratio but medial-to-lateral quadriceps ratios as well. One study showed that during the postcontact phase of foot strike during jump landings, women had less lateral hamstring activation than men [2]. However, more evidence suggests that women demonstrate a lower medial-to-lateral quadriceps ratio than men [68]. In fact, women seem to have lower activation in medial muscles of both the hamstring and quadriceps groups. Thus, their vastus medialis and medial hamstrings are deficient compared with their vastus lateralis and lateral hamstrings, respectively [64, 68]. The consequence of accentuated activation of the lateral knee joint muscles is the creation of a valgus knee. This finding has been evidenced as an unbalanced medial-to-lateral quadriceps to hamstring cocontraction index, which is believed to diminish a subject's ability to manage abduction loads that potentially increase the incidence of ACL tears in women [64]. Women, who cocontract their medial hamstrings and quadriceps less than men, have decreased frontal plane stability. In addition to accentuated frontal plane rotation at the knee characterized by valgus, women have been shown to produce more internal tibial rotation than men during jump landings, which also increases the risk of ACL injury [31].

9.6.3 Activation of Muscles Commonly Associated with the Hip Joint

Most studies assessing muscles associated with the hip found no gender differences in the magnitude of activation during jump landings. The gluteus medius has been assessed most frequently and shown to be similar between men and women prior to foot contact [57] and after foot contact during jump landings [57, 61, 62]. The absence of gender differences in gluteus medius activation was present with recreationally trained individuals [57], as well as more athletic subjects such as Division I collegiate soccer players [62], and did not change when subjects were exposed to 120 repetitions of leg press exercise in an effort to induce fatigue [61]. Thus, men and women seem to respond similarly to fatigue and activate the gluteus medius similarly during jump landings, regardless of the type of landing, training status, or fatigue. It is important to note that in some cases, significant gender differences in gluteus medius activity were not found despite mean and peak values that were 39.5–44.4% higher for women than men during the post-foot contact phase of the drop jump [57]. Additionally, during 10-cm horizontal jumps with single-leg landings, gluteus medius activity was 2.26 times higher in men than women, which was also not significantly different [63]. In some cases, gluteus medius activation was found to be higher in males than females when assessed for a 200-ms period after landing, though no significant differences were found for other muscles assessed [62]. While gender differences were sometimes not found for the gluteus medius, Zazulak et al. [58] showed that women activated the gluteus maximus less than men during drop-jump landings from 30.5 to 45.8 cm.

9.6.4 Summary

Studies examining muscle activation during jumping have investigated a variety of types of jumps and jump heights. A number of muscles have been assessed, though relatively little work has been done regarding the muscles that cross the ankle joint. While most studies examined these issues with recreationally fit young adults [2, 31, 57, 61, 63, 65–68], others used athletes [29, 58, 62] or adolescents [56, 59] as subjects. Some studies failed to show gender differences in muscle activation patterns for specific muscles groups [2, 31, 60, 61, 67]. However, differences in both the timing and the magnitude of activation have also been found [2, 20, 31, 54, 57–61, 66, 68]. These differences include delayed activation of muscles in the pre- and postcontact phase of jump landings for women, with higher total quadriceps activation and less hamstring activation after foot contact. Women may be laterally dominant [64] at the knee joint in the frontal plane, as evidenced by lower medial-to-lateral hamstring and quadriceps activation than men during jump landings [68]. Compared to men, women also disproportionately increase quadriceps activation compared to hamstring activation with increasing jump heights [54]. In some cases, women displayed less gluteus maximus activation than men [58]. Finally, some evidence shows that women also demonstrate less gluteus medius activation than men, though large mean differences were not statistically significant [63].

Critical Points

- A large number of studies have assessed gender differences in muscle activation during a variety of jump landings, including bilateral and unilateral conditions of a variety of jumps including drop jumps from a variety of heights.
- The literature is mixed with respect to gender differences in the timing and magnitude of muscle activation during jump landings.
- Some evidence shows differences in muscle activation timing characterized by women demonstrating delayed onset of the hamstring and quadriceps muscles in the precontact and post-foot contact phase.
- For studies showing differences in muscle activation, women demonstrate more quadriceps and less hamstring group muscle activation post-foot contact, during jump landings.
- In some cases, women produce less gluteus maximus activation than men, during jump landings.

9.7 Overall Summary

ACL injuries occur shortly after foot contact [18] during the first portion of the stance phase of dynamic activities such as cutting and landing from a jump. Unfortunately, during the first 40% of the stance phase, women demonstrate a less-coordinated movement pattern than men [19] at the same approximate time when ACL tension is the highest [18]. From the perspective of knee flexion during landing, ACL loading is the greatest at 22.0° for men and 24.9° for women [10]. ACL loading decreases with increased knee flexion [18], but women demonstrate less hip and knee flexion than men during tasks such as jump landing and cutting [1, 3–5, 21, 22].

9.7.1 Sagittal Plane Mechanics

Movement in all three planes of motion may be problematic for the ACL. It is likely that sagittal plane anterior shear due to the quadriceps activation is not enough to cause an ACL rupture [23]. It is not clear if the combination of ground reaction forces or exogenous forces, in addition to the sagittal plane quadriceps forces, is enough to damage the ACL. It is also necessary to consider the presence or absence of sufficient hamstring-mediated dynamic stabilization to oppose the quadriceps-induced anterior shear. The existence of quadriceps dominance of women was questioned in one review [69]. However, most research supports the idea that women are quadriceps dominant and/or hamstring insufficient during some athletic movements such as cutting [2, 46, 48, 49, 51, 52] and jump landings [2, 31, 52, 54, 58, 66]. In fact, in response to jumps of greater height and thus increasing intensity, women increase their quadriceps disproportionately compared to their hamstrings, more so than men [54]. Thus, increasing intensity of some forms of exercise increases the quadriceps dominance of women compared to men [54].

Additionally, the role of the muscles such as the gastrocnemius may aid in stabilization in the sagittal plane but have not been comprehensively studied. The gastrocnemius and other muscles that primarily affect the ankle joint have been seldom studied in the assessment of jump landings. However, the acute time course of activation of muscles such as the gastrocnemius may be faster than the hamstrings and quadriceps group muscles [7] and thus may have potential to exert quick dynamic control at the knee joint. Of additional concern is that for activities such as cutting, muscles whose primary function is to affect hip joint biomechanics have not often been studied. Thus, their contribution to sagittal plane biomechanics also requires consideration. Ultimately, mechanisms of ACL injury do not occur in only one plane (such as the sagittal plane) but are multiplanar.

9.7.2 Frontal Plane Mechanics

Gender differences in frontal plane mechanics are characterized by lateral femoral condyle compression and medial condyle lift-off [7, 70] resulting in frontal plane valgus. These phenomena are more typical for women than men and produce ACL loading high enough to cause rupture [28], with higher loads found for women compared to men [28]. This medial-to-lateral imbalance is due in part to the fact that women have a lower medial H:Q ratio compared to lateral H:Q ratio during jump landings [64, 68]. Women also have a medial-to-lateral gastrocnemius imbalance during cutting [48]. This imbalance contributes to the valgus knee condition, which is present in adolescents [20] and adults [22], and is exacerbated by the fact that women have greater ankle eversion [20, 26] and hip adduction [22, 25, 26] compared to men. Furthermore, from the perspective of the timing of these differences in frontal plane biomechanical issues, women appear to collapse more rapidly into valgus than men. Thus, muscle activation strategies that resist this collapse are recommended as part of an ACL injury prevention program.

In some cases, gender differences in gluteus medius have not been found during running despite large mean differences. It should be noted that the absence of statistical significance is not conclusive of the absence of gender differences, because it is possible that differences are present but the study design or instrumentation was not sufficient to identify them due to insufficient power and type II error [71]. While no gender differences in gluteus maximus activation were found during cutting in one study [52], muscles such as the gluteus maximus and medius are relatively unstudied for these movements, so their contribution to frontal plane biomechanics remains uncertain.

9.7.3 Transverse Plane Mechanics

Transverse plane movements in the lower extremity are likely during running and jump landings, but their role in cutting is more pronounced.

Medial-to-lateral gastrocnemius and hamstring muscle ratios influence transverse plane control during cutting due to the role of these muscles in stabilizing knee joint rotation [72]. During cutting, females have higher gastrocnemius activity than males [48] and a medial-to-lateral gastrocnemius imbalance [48], characterized by more lateral gastrocnemius activation during the pre-contact and early stance phase of the crosscut [49] and higher lateral gastrocnemius activity [48]. This laterality may be due to the transverse plane demands of the cut; however, it also may be representative of the lateral dominance that some researchers have found in the knee extensors and flexors of women, compared to men, who tend to be lateral dominant during jump landings as well [68, 72]. It should be noted that this laterality depends on the nature of the cutting task, as women demonstrate higher medial hamstring activation during the crossover cut [72]. Numerous researchers investigated muscle activation during cutting but did not examine muscles typically associated with the hip joint such as the gluteus medius and maximus. Thus, the contributions and potential gender differences of these muscles have yet to be elucidated.

9.7.4 The Optimal Muscle Activation Paradigm for Reducing ACL Injuries

In general, using EMG to assess muscle activation during dynamic movements sometimes results in large variability of subject performance and thus large standard deviations, which makes finding statistically significant differences problematic [42]. In the process of determining the presence of true gender differences, it remains necessary to rule out training status differences. This is true despite the fact that in some studies, subjects were athletes who played the same sport. It is possible that their resistance training and conditioning practices were different even if the demands of the sport were similar. While there are some inconsistencies in the literature, the current evidence suggests the existence of some differences between male and female athletes in muscle activation which may be due in part to sex differences in the biomechanics of running, cutting, and landing. Table 9.1 represents the required muscle activation for reducing ACL injuries.

Table 9.1 Required muscle activation for reducing ACL injuries

Biomechanical concern	Required muscle activation in response to biomechanical concern	Rationale
Eversion	Tibialis anterior Tibialis posterior	Increase dynamic control by training inversion to limit eversion
Pronation	Adductor hallucis Extensor hallucis longus Flexor hallucis longus Tibialis anterior Tibialis posterior	Increase dynamic control by training adductors and inverters to limit pronation
Sagittal plane tibial translation	Gastrocnemius Hamstring Higher hamstring-to-quadriceps activation ratios	Increase posterior drawer force on the tibia to reduce anterior shear
Internal tibial rotation	Biceps femoris	Increase dynamic control to reduce extreme range of motion of internal rotation
External tibial rotation	Semimembranosus Semitendinosus Sartorius Popliteus Gracilis	Increase dynamic control to reduce extreme range of motion of external rotation
Frontal plane valgus knee	Semimembranosus Semitendinosus Vastus medialis oblique Medial head gastrocnemius	Decrease knee join lateral dominance, which contributes to the valgus knee
Hip adduction	Gluteus medius Gluteus minimus Piriformis Tensor fascia latae	Train hip abductors to limit hip adduction
Hip internal rotation	Gluteus maximus Obturator externus Obturator internus Piriformis Quadratus femoris	Train hip external rotators to limit hip internal rotation

Exercises that optimally activate these muscles that may provide dynamic control and potentially reduce ACL injuries have been described. For example, the biceps femoris is more highly activated during closed kinetic chain exercise such as the Russian curl, stiff leg dead lift, single-leg stiff leg dead lift, and good morning compared to other closed kinetic chain exercises such as the squat [73]. Close kinetic chain exercise such as the dead lift produces more hamstring activation than other exercises characterized by hip and knee extension [74]. The dead lift, compared to other closed kinetic chain exercise such as the lunge, squat, and step-up, optimally activates the lateral and medial hamstrings [75]. Unfortunately, the dead lift does not show preferential activation of the medial hamstrings compared to lateral hamstrings; thus, it is hard to say if this exercise can be used to reduce frontal plane laterality or external tibial rotation. Additionally, open kinetic chain exercises such as the leg curl activate the biceps femoris at high levels of its MVC [73]. The development of higher H:Q ratio may have some value and should include the aforementioned hamstring-dominant resistance training exercises. Conversely, the H:Q ratio would be impaired by exercises such as the leg extension which produces comparatively little hamstring (compared to quadriceps) activation [74]. Resistance training using exercises known to activate the hamstrings [73] was more effective than plyometric training at improving H:Q ratio during cutting and jump landings (data from the author's laboratory), even when using plyometric exercise with the greatest mean hamstring activation [76].

Hip abductors, such as the gluteus medius, are most active during exercises with a unilateral component, such as the step-up or lunge compared to bilateral exercises such as the dead lift and squat [75]. Of these, the step-up produces the greatest mean EMG [75]. Variations of the step-up have been studied using six repetition maximum loads. In addition to the gluteus medius, some evidence shows gluteus maximus activation is greatest during the step-up, lunge, and dead lift, compared to the squat [75]. Specific strategies designed to increase gluteus maximus activation during jump landings, such as applying a resistance band to the lower shank, were effective in increasing hip abductor activation during jump landings but not without concomitant reductions in initial hip flexion angle, initial hip abduction angle, and maximum knee flexion angle [77]. Select single-leg plyometric exercises, such as the single-leg hurdle hop, produced more gluteus maximus, gluteus medius, and hamstring activation than other plyometric exercises [78].

Muscles that cross the ankle joint, such as the gastrocnemius, may be affected by foot position during training. Medial gastrocnemius activation may be enhanced with an externally rotated foot, whereas lateral gastrocnemius activation is increased with internal rotation of the foot during heel-raise exercises. The activation of other muscles that cross the ankle such as the tibialis anterior and posterior, and deep rotators of the femur, for example, has not been assessed during exercise modes.

Critical Points

- Research shows that women are quadriceps dominant and/or hamstring insufficient during some athletic movements such as cutting and during jump landings.
- In response to jump landings from increasing heights, thus increasing intensity, women activate their quadriceps disproportionately compared to their hamstrings, more so than men.
- Women compared to men seem to have a lateral dominance of knee joint muscles which increases the valgus knee condition.
- The predisposition to the valgus knee condition is present for both adolescents and adults females.

- The valgus knee condition is due to greater ankle eversion and hip adduction of women, compared to men.
- Women appear to collapse more rapidly into valgus, compared to men.
- Gender differences in the role of the gastrocnemius, gluteus medius, and gluteus maximus are understudied during movements such as cutting and jumping.
- Neuromuscular training may help females reduce undesirable biomechanics during running, cutting, and jumping.

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10 Proximal Risk Factors for ACL Injury: Role of Core Stability

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Abstract

This chapter describes the relationship of core stability to ACL injury. The terms core, stability, and core stability are defined. Measurement techniques and training for core stability are presented. Preliminary evidence of a connection between active and reactive activations of the core muscles and knee loading patterns relevant to ACL injury are described.

10.1 Introduction

Core stability is a popular term in both the scientific literature and popular media because it is almost universally believed that better core stability will result in enhanced performance as well as improve injury prevention and treatment strategies [1, 2]. However, the term itself is vague and is used in various ways in the literature, making it difficult to synthesize the current state of knowledge in this area. In order to properly discuss core stability and its relation to anterior cruciate ligament (ACL) injury, the terms core, stability, and core stability must first be defined.

10.1.1 Core Defined

The extent of the core region of the body itself has not been defined consistently across the literature. Some authors include all of the muscles crossing the hip joint, lumbar spine, and inferior thoracic spine, colloquially referred to as nipples to knees. This latter definition may be too broad to isolate and examine function, because in sports where ACL injury risk is high, the hip muscles often act as prime movers of the lower extremity, while the muscles crossing the lumbar spine primarily act to stabilize the spine in a relatively static position. For example, the gluteal muscles contribute significantly to total power generation and absorption in jumping, landing, and lateral sliding, while the hip flexors contribute to kicking. In contrast, the muscles crossing the lumbar spine limit its motion, thereby allowing the athlete to maintain proper posture and appropriately transfer energy between the arms and legs. Therefore, we define the core as the region of the body bounded by the pelvis and diaphragm which includes the muscles of the abdomen and lower

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back. By this definition, the muscles of the core are responsible for the position and movement of the trunk.

10.1.2 Core Stability Defined

According to the *Merriam-Webster Dictionary*, stability may be defined as "the property of a body that causes it when disturbed from a condition of equilibrium or steady motion to develop forces or moments that restore the original condition" [3]. It follows, then, that "core stability" is the ability of the core, or the muscles of the abdomen and lower back, "to maintain or resume a relative position [or trajectory] of the trunk after a perturbation" [4]. This perturbation can come from sources external to the body (such as other players, obstacles, or equipment) or from movement of the extremities. Core stability is a dynamic quality rather than an intrinsic property of the system; that is, the muscles involved must continually react to changing loading conditions and postures to maintain stability [5]. To achieve this stability and maintain position or trajectory in the presence of external forces that are continuously changing during athletic maneuvers, appropriate strength, endurance, and muscle activation timing and intensity are all required. Without any one of these attributes, core stability cannot be efficiently maintained.

The core is responsible for positioning the trunk and upper body over the lower extremity. Since the trunk and upper body account for more than half an individual's body weight [6], poor trunk control and core stability could place this mass in a position that results in adverse loading of the knee, leading to injury (see Sects. 10.4 and 10.5 for further discussion). Core stability may also contribute to athletic performance, by providing "proximal stability for distal mobility" [1]. Hodges and Richardson demonstrated that core muscle activation precedes activation of muscles responsible for moving the lower extremities [7]. This sequence of muscle activation has, therefore, been thought to provide a stable base for limb movement, making the movement more efficient and effective. This theory is further supported by recent studies of professional baseball pitchers by Chaudhari et al. which showed that lumbopelvic control was associated with pitching performance [8] and risk of time-loss injuries [9]. Pitchers with better control of the lumbopelvic region in the first study pitched significantly more innings and had significantly fewer walks plus hits per inning pitched over one season [8]. In the second study, pitchers with the poorest lumbopelvic control were 3.0 times as likely to miss 30 or more days due to injury during the season [9]. While these data supported the connection between core and upper extremity movement, they also suggest that the role of the core in providing that same stable base for better lower extremity control and reduced ACL injury risk merits further exploration.

Critical Points

- Core: the region of the body bound by the pelvis and diaphragm, which includes the muscles of the abdomen and lower back.
- Core Stability: the ability of the core to maintain or resume relative position of the trunk after a perturbation or disturbance.
- Core stability is a result of the combined effects of strength, endurance, and muscle activation timing and intensity.
- Concentration of half the body's mass in the upper body creates a theoretical basis for the core to contribute to both function and lower extremity injury risk.

10.2 Traditional Core Assessments and Training

Because strength, endurance, and activation patterns all contribute to core stability, measurements and training related to core stability vary widely in the literature and in practice. Due at least in part to the lack of appropriate tools to measure stability in the clinical setting, most assessments of the core have focused instead on strength and endurance. Both the United States Army Physical Fitness Test and Presidential Physical Fitness Test quantify how many times a subject can perform a sit-up in a given amount of time [10, 11]. The Army Physical Fitness test determines how many sit-ups a soldier can perform in 1 min, while the Presidential Physical Fitness test measures how many curl-ups or partial curl-ups a subject can perform in 1 min. These tests theoretically require both strength and endurance of the core to achieve a high score, but they do not provide any objective assessment of the muscle activation patterns that would contribute to core stability.

Considering the primary role of the core in maintaining postural stability (i.e., holding proper posture over time), several researchers have employed tests where subjects must maintain a static position against gravity for as long as possible. Variations of trunk endurance assessment include the prone-plank, side-bridge, and flexor endurance tests (Fig. 10.1) [12, 13]. In the

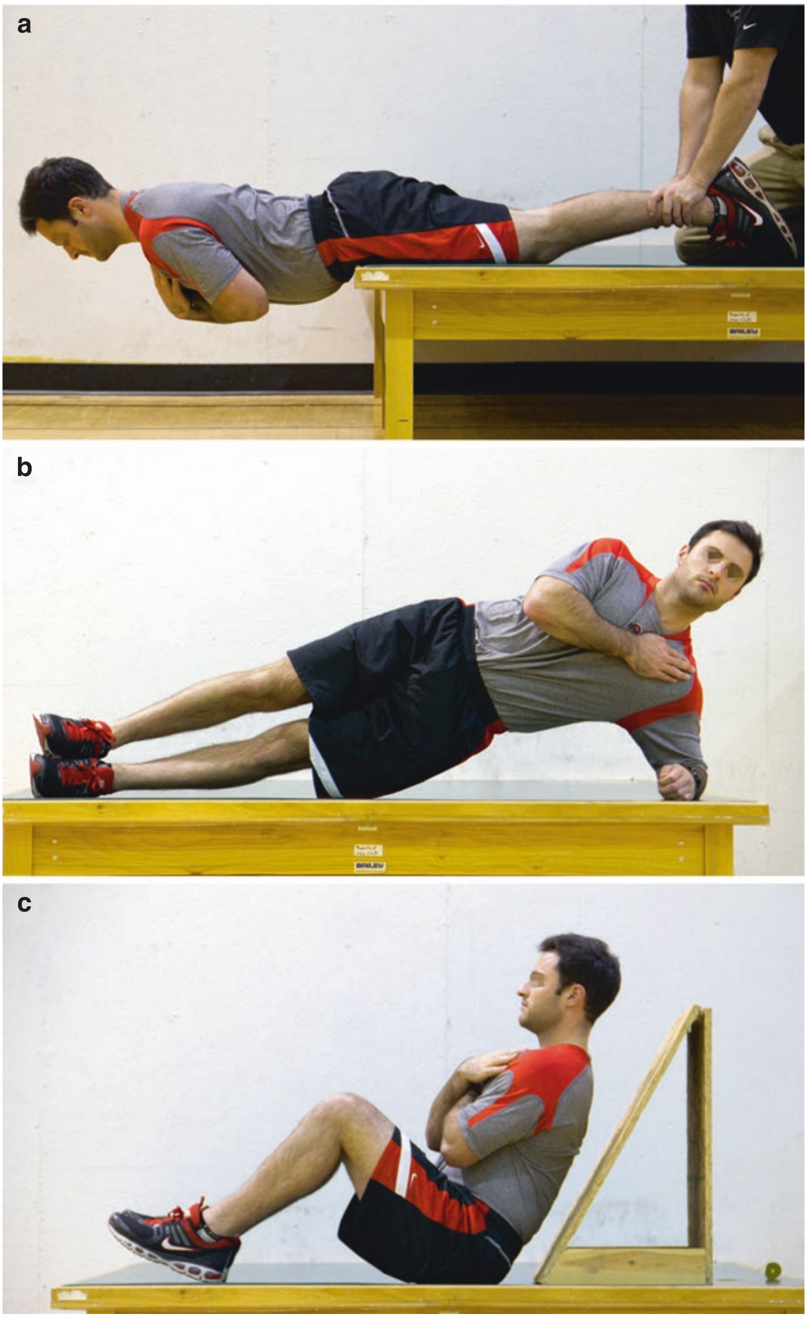

Fig. 10.1 Prone-plank (**a**), side-bridge (**b**), and flexor endurance (**c**) tests used to assess trunk endurance

clinical setting, these tests are relatively easy to administer and ensure that subjects are using proper technique. In the prone-plank test, subjects lie prone (face down) with their feet and/or legs secured to a table. The upper body is cantilevered off the edge of the table and parallel to the floor. During the side-bridge test, subjects support themselves on their feet and one elbow, keeping the body in a straight line with the supporting elbow side facing down. Finally, during the flexor endurance test, subjects sit with knees and hips flexed at approximately 90° and their upper body 60° from the test bed. For each endurance test, subjects are instructed to hold the desired position as long as possible, and the hold time is recorded.

Positional control of the lumbar spine, another aspect of core stability, is also commonly tested in a supine position (lying face up) using what is commonly known as the "Sahrmann test" [14]. In this test (Fig. 10.2), an air bladder is placed under the lumbar curve, and changes in air pressure are observed while subjects perform arm and leg raises of increasing difficulty [13–15]. Subjects are instructed to maintain the curve throughout the movements. Increased or decreased air pressure in the bladder indicates a lack of control of spine movement. The test can also be performed with the tester's hand substituted for the air bladder, where the tester qualitatively assesses whether the lumbar spine rises off or presses into the table. This test comes closest to measuring core stability as defined in Sect. 10.1, but it has the drawback of only measuring core stability in the supine position for specific, controlled movements. Nevertheless, this test has become extremely common in the clinical setting because it is easy to administer and can be performed by all patients, even if they lack the core strength to perform the previously mentioned sit-ups or endurance tests.

By design or coincidence, typical training programs for core stability have followed similar principles to the abovementioned tests for core stability. In the US Army, soldiers train with sit-ups to be able to perform well on their regular fitness tests, in spite of the recommendations to limit sit-ups due to dangerously high spinal compression loads, especially when performed for speed [16–18]. In other settings, similar movements have been popular in training regimens throughout sports and in the general population, so much so that hundreds of products are currently available on the market that tout their ability to help people improve their abdominal strength and endurance by assisting the individual to perform the exercise correctly even if he/she lacks the strength and endurance to perform unassisted sit-ups [19].

Training programs for low back rehabilitation and for running injury prevention often focus on stabilization exercises similar to the prone-plank,

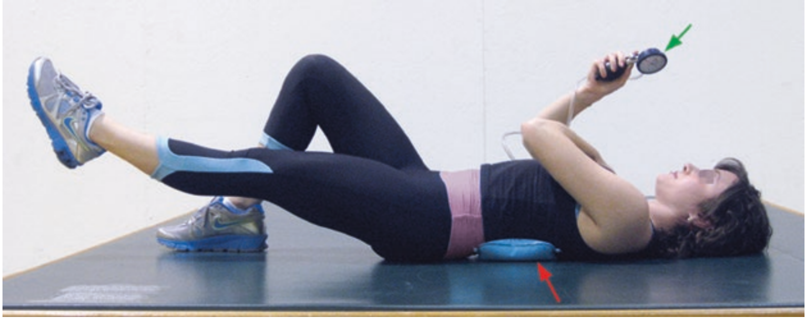

Fig. 10.2 Clinical test of supine trunk control. An air bladder is placed under the lumbar curve (red arrow) and inflated to a known pressure as indicated by a pressure gauge (green arrow). Subjects perform arm or leg lifts while attempting to maintain the curve, and increased or decreased air pressure in the bladder indicates a lack of control of spine movement. This apparatus can also be used as biofeedback during training exercises where the goal is to minimize changes in pressure

side-plank, and flexor endurance tests [20–22], though hold times are not usually the main objective in these cases. Typically challenging progressions in the exercises include the addition of limb movement and decreased support or increased weight while keeping the requirement of a stable, fixed trunk [22–24]. Increasingly difficult leg raises are often incorporated into exercise programs in conjunction with the bladder to provide feedback on lumbar position to increase strength and control of the core [20, 25]. In the latter stages of training for performance, athletes are asked to simultaneously move their upper and lower extremities with increasing range of motion and velocity while maintaining that stable, fixed trunk [21].

Several successful ACL injury prevention programs have included components of core stability training [26–33]. However, it remains controversial whether improving core stability is a necessary component to reduce lower extremity injury risk, as well as whether improving core stability can be effective in isolation or only when incorporated into a comprehensive injury prevention program. A meta-analysis of ACL injury prevention programs [34] concluded that preventative neuromuscular training programs that included proximal control exercises were more effective at reducing ACL injury rates than programs that did not include these exercises (odds ratio, 0.33 and 0.95, respectively). The proximal exercises in the training programs varied from sit-ups and push-ups to upper body resistance training. In addition to the proximal exercises, these training programs also incorporated exercises focused on balance, plyometrics, and strength. While a reduced incidence of ACL injuries was observed with these programs, it is impossible to attribute the reduction of injury to any single component of the exercise programs because they were designed in a trial-and-error fashion rather than by systematic addition/removal of individual exercises to determine each exercise's role on injury incidence or functional changes. Nevertheless, the evidence accumulated through an increasing number of intervention studies that have differences in exercises suggests that training of the core is an important component in reducing the incidence of ACL injury.

Critical Points

- A large variety of core training and assessment protocols are being used to evaluate and train aspects of the core.
- Training programs incorporating core-specific exercises have been successful at reducing ACL injury risk, but the extent to which the core-specific exercises influenced the reduction in injury risk in these studies remains unclear.
- Many different core-specific exercises have been utilized in successful training programs, but it is unknown which of these exercises are effective at training core stability or at reducing ACL injury risk.

10.3 Prospective Evidence Linking the Core to ACL Injuries

A growing number of prospective studies have investigated the link between aspects of core stability and ACL injuries. The first, conducted by Leetun et al. [35], examined the prone-plank and side-bridge core endurance tests in intercollegiate athletes as potential predictors of lower extremity injury. These investigators found no significant association between core muscle endurance and future injury status.

In contrast to Leetun et al.'s examination of core endurance, two prospective studies conducted by Zazulak et al. [4, 36] examined core stability as defined in Sect. 10.1. These studies highlighted a potential connection between core stability and female ACL injuries. A total of 140 female and 137 male varsity athletes with no prior history of knee injury were included. Knee injury was defined as any ligament, meniscal, or patellofemoral injury diagnosed by a university sports medicine physician. One study characterized the ability of the individual to return the torso to its starting position after being rotated in the transverse plane, while the other characterized the ability of the individual to halt movement of the torso after a rapid perturbation.

In the first of these two studies, Zazulak et al. quantified core proprioception using an apparatus originally designed by Taimela et al. to produce passive motion of the lumbar spine in the transverse (horizontal) plane (Fig. 10.3) [4, 37]. In this test, subjects sat on a seat driven by a motor that generated motion in the horizontal plane while their upper body was fixed to a backrest that did not rotate with the seat. The seat was rotated 20° by the experimenter, held for 3 s, and then released. After release, subjects were asked to rotate to the original, neutral position. When subjects perceived that they had reached this position, the error between the actual original position and the current position was calculated.

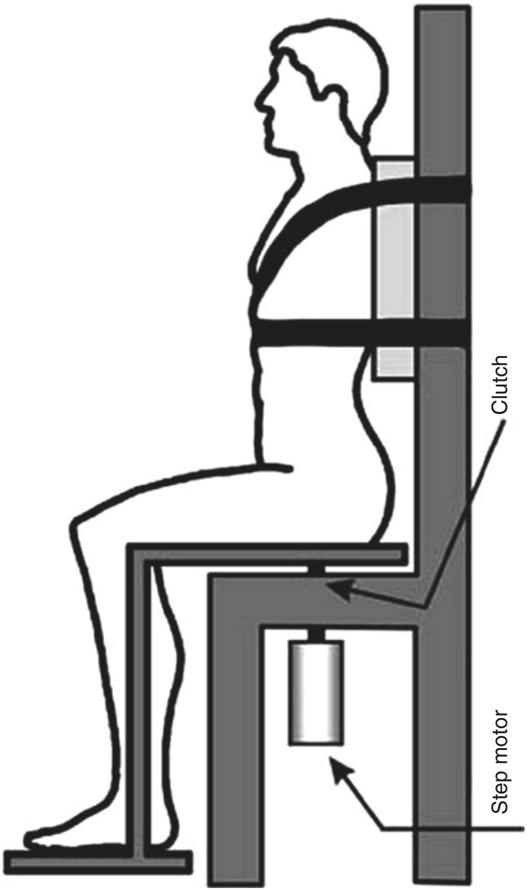

Fig. 10.3 Apparatus used by Zazulak et al. [4] to test core proprioception. The stepper motor rotates the seat 20°, holds for 3 s, and then is released using the clutch. Subjects rotate themselves back to what they perceive is the original, neutral position. The error between the perceived and actual positions is measured (Reproduced from Zazulak et al. [4]; with permission from SAGE Publications, Inc)

In the second study, Zazulak et al. quantified isolated trunk control following sudden unloading in three directions (flexion, extension, and lateral bending; Fig. 10.4) [36]. In this investigation, subjects were placed in a semi-seated position with their pelvis secured while still allowing their upper body to move freely. A cable was attached to a chest harness at approximately the level of the fifth thoracic vertebra. Subjects pulled isometrically against the cable at a constant force level corresponding to 30% of the maximum isometric trunk strength for an average healthy man (108 N) or woman (72 N). The resisted force was suddenly released at random time intervals by deactivating an electromagnet anchoring the cable. Angular displacement of the trunk after the release was calculated. Subjects were instructed to minimize movement post-release so increased displacement was associated with a decrease in trunk control.

During the 3-year posttest follow-up period for these two studies [4, 36], of the 277 (140 female) athletes that participated in both studies, 25 (11 female) sustained knee injuries, and 6 (4 female) sustained ACL injuries confirmed with magnetic resonance imaging. The trunk proprioception study included both meniscus and ligament injuries in a third injury category (16 total, 7 female), while the trunk control study only included ligamentous injuries (11 total, 5 female).

Results from the proprioception study indicated that women who later experienced knee and ligament/meniscus injuries had significantly greater repositioning errors than uninjured females ($P = 0.006$ and $P = 0.007$, respectively) [4]. Further, the authors found that for every degree of increased error, a 2.9-fold increase in the odds ratio of knee injury ($P = 0.005$) and a 3.3-fold increase in the odds ratio of ligament/meniscus injury ($P = 0.007$) were observed. No significant difference was observed between repositioning error of ACL injured and uninjured

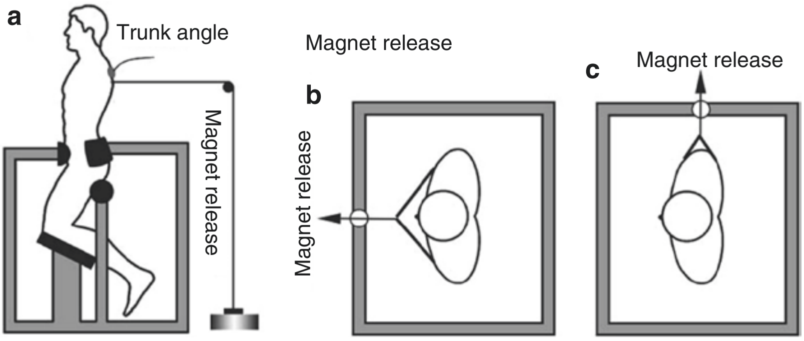

Fig. 10.4 A subject positioned in a multidirectional, sudden force release apparatus used by Zazulak et al. and Jamison et al. to quantify trunk control [23, 36, 70]. Subjects pulled in trunk flexion (**a**), extension (**b**), and lateral bending (**c**) against the cable with a prescribed force. Resisted force was suddenly released by deactivating the magnet, and the subsequent trunk angular displacement was recorded (Reproduced from Zazulak et al. [36]; with permission from SAGE Publications, Inc)

females, but the sample size (only four ACL injuries) was too small to draw definitive conclusions.

Results from the trunk control experiment indicate that ligament-injured female athletes demonstrated greater maximum lateral displacements than uninjured female athletes ($P = 0.005$) [36]. When the results were collapsed across gender, maximum lateral displacement was significantly greater in all three injury classifications, including ACL injuries.

An Austrian study of competitive ski racers by Raschner et al. [38] demonstrated the potential for isometric core strength as a factor in ACL injuries. By combining regular prospective screening and injury tracking over a 10-year period of members of the Skigymnasium (a junior development program for elite alpine skiers), the authors identified isometric supine trunk flexion and prone extension strength as significant factors in multivariate logistic regression models for both male and female athletes aged 14–19. In both males and females, the absolute flexion force to absolute extension force ratio (FLE:EXT R) was a significant though moderate contributor (male odds ratio 0.24, female odds ratio 0.54). In group comparisons between injured and noninjured males, FLE:EXT R was significantly different ($P = 0.007$), as were summed trunk flexion and extension forces relative to body mass ($P = 0.013$). However, in the female athletes, the absolute sum of trunk flexion and extension forces was significantly different between groups ($P = 0.009$). Given the likely importance of having adequate strength to provide core stability during high-speed ski racing where sudden and extreme external forces are present, the significant core strength findings in this study are consistent with a need for good core stability in ski athletes. The future addition of core stability measures may provide additional insight and additional predictive value for ACL injuries in this population.

Most recently, Dingenen et al. [39] prospectively followed 50 elite female soccer, handball, and volleyball athletes for 1 year to examine whether their single-leg drop vertical jump technique was associated with future knee injuries. Using two-dimensional frontal video, these investigators measured and summed the knee valgus angle and the trunk angle at peak knee flexion of the landing relative to horizontal from the ipsilateral side (KVLTM). A perfectly vertical trunk and neutral knee would give a value of 180°, while greater knee valgus and greater ipsilateral trunk lean would each lead to smaller values. Seven athletes suffered noncontact knee injuries (four ACL ruptures, three other), and these athletes demonstrated significantly smaller KVLTM than noninjured athletes, indicating either greater ipsilateral trunk lean, greater knee valgus, or both. Receiver operating characteristic analysis demonstrated that the KVLTM had significantly greater area under the curve than random prediction with both the future injured and noninjured legs. In this experiment, the KVLTM measure was considered a measure of core stability, because the external impulse from foot impact created a perturbation to both the hip and trunk and the amount of deflection before the participant was able to arrest frontal motion was assessed.

Results from these four studies [4, 36, 38, 39] suggest a role for trunk proprioception and strength and motor control (all contributing factors to core stability) in knee and ligamentous injury risk for both male and female athletes. Zazulak's and Dingenen's tests were designed as surrogates for how an athlete responds to the conditions and demands of play in his/her sport. However, it remains unknown whether these factors have a direct role in ACL injury risk or whether they are surrogates for systemic proprioception and control. Under the former hypothesis, core stability could have a direct role in ACL injury risk by leading to increased or decreased strain on the ACL. Under the latter hypothesis, an individual with superior trunk proprioception and control would also have better proprioception and control of the hip, knee, and ankle, which could be the direct cause of reduced biomechanical loading on the knee and reduced ACL injury risk.

Critical Points

- Decreased transverse plane trunk proprioception has been associated with increased knee and ligament, not ACL, injury risk in females.
- Decreased lateral trunk control has been associated with increased risk of injuries to the knee, including the ACL, in female athletes.
- Decreased lateral trunk control has been associated with increased ACL injury risk in male and female varsity athletes.
- Decreased sagittal trunk isometric strength and flexion-extension strength imbalances have been associated with increased ACL injury risk in male and female elite alpine ski racers.
- It remains unknown whether trunk control, proprioception, and strength cause ACL injury risk to increase or whether the association is merely coincidental.

10.4 Video Observations of Core Motion During ACL Injury Events

Most clinicians and researchers have observed an ACL injury occur at some point in time, either live or on video. It is impossible to know exactly when the injury occurred and rare to have the ideal view(s) of the event to accurately reconstruct the body kinematics during the event. Nevertheless several authors have reported comparisons between observed motions of the core during injury events versus noninjury events.

Hewett et al. [40] reported lateral trunk angles in female and male athletes during 23 ACL injury events where the camera angle approximated a coronal view, the foot was clearly visible contacting the ground, the athlete was unobscured, and minimal contact with other players was observed. They compared the trunk angles to control athletes performing similar tasks. The measurement was made by first choosing the frame of video that approximated initial foot contact with the ground and the five subsequent frames. In each of the five frames, trunk angle was estimated by the angle between a line connecting the greater trochanter to the ipsilateral acromioclavicular joint and a vertical line. This measurement was compared between female injured and male injured and between female injured and female controls using a repeated measures ANOVA including all five time points. The authors reported that female injured experienced greater lateral trunk lean over the injured leg than male injured and trended to greater trunk lean when compared to female controls.

Sheehan et al. [41] examined sagittal trunk angles, as well as the distance between the base of support and estimated center of mass in female and male athletes during 20 ACL injury events where a sagittal view was available, following similar criteria for inclusion of videos as Hewett et al. [40]. Again, these events were compared to athletes performing similar maneuvers in noninjury events. For this analysis, the authors drew ellipses to approximate the trunk, thigh, shank, and foot in the video frame closest to initial foot contact. Sagittal trunk angle was estimated as the angle between the major axis of the trunk ellipse and vertical. The center of mass was estimated as the center of the trunk ellipse. The horizontal distance between the center of mass and point of contact between foot and ground (COM_BOS) was also estimated. Both trunk angle and COM_BOS were observed to be significantly different between injured and uninjured athletes, with the injured athletes having more upright posture and stretching the foot further in front of the center of mass.

Stuelcken et al. [42] examined trunk and knee angles in female netball athletes during 16 ACL injury events that occurred during televised games at the ANZ championship competitions from 2009 to 2015. Using previously reported criteria and consensus scoring among biomechanists, a skill acquisition specialist, and a physiotherapist, the authors identified key characteristics of motions. These included the movement just before injury, the task the athlete was attempting to achieve, the trunk motion just before the injury, and the knee motion just before, during, and after the injury. All 16 injuries involved either no contact with the injured athlete, indirect contact to another part of the body, or contact just before the injury event. In 13 cases, the athlete was attempting to receive or intercept a pass or compete for a loose ball. In 11 cases, the athlete performed transverse trunk rotation away from the leg about to be injured, and in 7 of those 11 cases, the athlete also tilted the trunk laterally toward the side of the leg about to be injured (ipsilateral trunk lean).

The results of these studies must be considered in light of the limitations inherent to two-dimensional video including video quality, video angle, and measurement accuracy, as well as the limitation that the timing of the ACL injury itself is unknown. Nevertheless, these results are consistent with the theoretical basis for the role of the core that placement of the relatively large mass of the upper body may influence knee loading and thereby injury risk. Moreover, these findings suggest the need for biomechanical studies to determine whether position of the core influences knee loading.

Critical Points

- Video analysis of ACL injury events provide a unique opportunity to observe kinematics that may be related to the injury.
- Limits to spatial and time resolution of standard video make it impossible to conclusively determine injury mechanisms.
- Greater lateral trunk lean may be related to ACL injury in women based on video observation.
- More upright posture and position of the trunk center of mass further behind the foot in the sagittal plane may be related to ACL injury in both men and women based on video observation.

10.5 Biomechanical Evidence Linking the Core to Knee Loading: Cross-Sectional Studies

As detailed in Sect. 10.3, most prospective research on core stability and ACL injury has focused on empirically identifying associations between core stability measurements and ACL injury incidence. Studies like these are critical to establish the extent of the injury problem, which is commonly accepted as the first step in preventing sports injuries [43]. However, as previously mentioned, these studies still leave unanswered the question of whether core stability has a direct mechanical effect on the knee joint and the ACL. Recent video observations of ACL injury events suggest that position of the trunk may influence ACL injury risk [40–42], but due to the limitations of two-dimensional video analysis, they serve best as a motivation for developing hypotheses that can be tested more rigorously using more sophisticated techniques. Along these lines, recent work using motion analysis and computer simulation has begun to explore the direct biomechanical connection between core stability and knee loading in greater detail.

Several cross-sectional studies have linked positioning of the upper body to knee loading parameters which have been identified as risk factors for ACL injury. In particular, these studies examined peak external knee abduction moment (pEKAbM) as the knee loading outcome of greatest interest during side-step cutting maneuvers and drop landings, which are known to be high risk for ACL injury in field and court sports [40–42, 44, 45]. An external knee abduction moment occurs when the forces generated between the ground and the lower limb act to push the knee medially into a more valgus alignment. Increases in pEKAbM were associated with ACL injuries during a prospective study in a population of female adolescent athletes [46]. Increasing knee abduction moments have also been associated with increased strain (elongation) of the ACL in both cadaver knees [47, 48] and computer simulations [49, 50].

Chaudhari et al. [51] used markered-motion capture techniques and inverse dynamics to estimate the pEKAbM of 11 subjects (6 women, 5 men; mean age of 22.3 ± 3.5 years) performing 90° cuts away from the plant-side foot for 4 arm conditions (holding a lacrosse stick with both hands, holding a football with the cut-side arm, holding a football with the plant-side arm, and a control condition where nothing was held). Results indicated that constraining the arms during a cutting maneuver can increase pEKAbM when compared to a baseline condition where the arms are not constrained. When the plant-side arm was forced to hold a football, the pEKAbM increased 29% ($P = 0.03$). When subjects held the lacrosse stick with both hands, the pEKAbM increased 60% ($P = 0.03$).

Dempsey et al. [52] examined 15 healthy males performing a 45° side-step cutting maneuver using their own technique but also when attempting to lean/twist in the frontal plane or transverse plane and attempting to alter foot placement in the frontal plane or transverse plane. When altering motion of the trunk, several differences in knee moments were observed. Trunk lean in the opposite direction from the cut resulted in 38% higher pEKAbM than leaning in the same direction as the cut ($P < 0.05$). Trunk twist resulted in 53% higher peak tibial internal rotation moment (pTIRM) than the natural condition ($P < 0.05$). pTIRM is an external moment that would act to rotate the tibia internally with respect to the femur, and increases in pTIRM have also been associated with increases in ACL strain [50] and force [53].

In another study using markered-motion capture and inverse dynamics to estimate knee moments, Jamison et al. [54] used similar data collection and reduction techniques on a similar population (14 female, 15 male, no prior history of ACL injury). However, in this study, an unanticipated 45° cut was examined to better mimic the environment on the field when an athlete's movements are dictated by the game play. Unanticipated cutting situations have also been shown to lead to higher knee abduction moments than preplanned movements [55]. In addition to calculating pEKAbM and pTIRM, ipsilateral trunk lean (lateral angle away from direction of the cut, termed "outside tilt" in the study) was calculated. Using multiple regression analysis to examine the relationship between moments and ipsilateral trunk lean as continuous variables within each individual, this study observed that pEKAbM was positively associated with ipsilateral trunk lean ($P = 0.002$), while pTIRM was negatively associated with ipsilateral trunk lean ($P = 0.021$). A positive association between ipsilateral trunk lean and pEKAbM suggests that as torso angles increase, so does pEKAbM, which would be expected to increase strain in the ACL and therefore place it a greater risk for rupture. The negative association between ipsilateral trunk lean and pTIRM suggests that as ipsilateral trunk lean increases, pTIRM decreases, protecting the ACL from strain and danger of rupture. However, these peaks in pEKAbM and pTIRM did not occur at the same time, so the effect of increased ipsilateral trunk lean on pEKAbM would be expected to increase the risk of ACL injury through an excessive valgus moment mechanism. More recently, other cross-sectional studies using similar measurement techniques that examined between-subject differences during 90° cutting maneuvers [56], lateral reactive jumps [57], and single-leg drop vertical jumps [58] all found similar results, with ipsilateral trunk lean having a significant association to pEKAbM.

Donnelly et al. [59] applied computer simulation techniques to baseline data from markered-motion analysis of nine male athletes with high pEKAbM during unanticipated 45° side-step cutting maneuvers to estimate how an athlete might optimize his whole-body movement to reduce pEKAbM. The open-source simulation software OpenSim with a scaled generic model was used to perform the simulations. In the simulations, adjustments to motions of all joints were permitted as long as they reduced pEKAbM while not altering foot position relative to the ground more than 30 mm. While each of the nine subject-specific simulations began with unique kinematics and kinetics, the optimization resulted in the "strategy" of repositioning the whole-body center of mass medially and anteriorly in all nine simulations.

The above findings suggest that subjects may be capable of using their arms and core to protect their knee from adverse loading patterns and, potentially, from ACL injury. Conversely, trunk lean or twist away from the direction of cutting, an upright posture, and constrained arms may all lead to increased knee loading and, therefore, increased risk of ACL injury. These biomechanical results are consistent with the video observations of ACL injury events described in the previous section: lateral trunk lean [40, 42], upright posture [41], and a more posterior center of mass relative to the foot [41].

Frontal motion is not the only dimension in which cross-sectional studies have shown an association between trunk motion and ACL injury risk. In vivo, simulation, and cadaveric studies have demonstrated that both trunk flexion and transverse plane trunk rotation can contribute to adverse knee loading, ACL force, and ACL strain. Shimokochi et al. [60] demonstrated that, during a single-leg drop landing, landing with a forward trunk lean decreased anterior shear force at the knee and increased knee flexion, both protective of the ACL. Kulas et al. [61], using in vivo and modeling techniques, showed that an increase in forward trunk lean during a single-leg squat decreased ACL ligament force by 24% and ACL strain by 16%. Frank et al. [62], in an in vivo three-dimensional analysis of side-step cutting, corroborated Stuelcken's two-dimensional video results previously discussed [42]. In the three-dimensional analysis, an increase in transverse plane trunk rotation away from the stance limb was associated with a decrease in pEKAbM, which would serve to protect the ACL. Contrary to previous findings, however, an increase in forward trunk lean was associated with an increase in pTIRM, which would suggest an increase in ACL injury risk. In an in vivo and simulation study of ski jump landing, trunk orientation accounted for 60% of the variance in ACL force, with increased trunk extension being associated with increased ACL force [63]. Finally, in a study combining cadaveric, in vivo, and simulation biomechanics, trunk flexion uniquely accounted for nearly half the variance of ACL strain by extrinsic factors, with an increase in trunk flexion being associated with a decrease in ACL strain [64]. This collection of studies suggests that a moderate forward trunk lean can help protect the ACL during dynamic motion.

One of the many questions left unanswered by these studies is the role of muscle coordination patterns in the observed associations between upper body movement and knee and ACL loading. One potential explanation of the observed outside torso tilt is that muscle activation of the core lags behind the lower extremity, while an alternative explanation is that athletes actively choose to pull the torso into the outside tilt position as preparation for a change of direction. Jamison et al. [65] attempted to answer this question by examining muscle activation differences between left/right and anterior/posterior pairs of muscles during cutting maneuvers. Left/right activation patterns of the obliques and lumbar extensors were not associated with outside torso tilt during unanticipated cutting maneuvers, suggesting that the athletes were not actively attempting to achieve that position. In contrast, coordinated contraction of both left and right lumbar extensors was associated with a stiffer torso and higher pEKAbM, suggesting an active strategy by some athletes to maintain an upright trunk that may be detrimental to the knee. These latter results were consistent with another study by Haddas et al. [66] in which athletes were asked to consciously contract the abdominal muscles just before landing from a jump. Increased volitional preemptive abdominal contraction (VPAC) was associated with decreased pEKAbM and with a relative increase in anterior trunk muscle activations compared to posterior trunk muscles. This result suggests that some athletes are actively trying to maintain an upright posture in the absence of VPAC, which, again, may be detrimental to the knee. The results from these studies further support the theory mentioned previously that a forward trunk lean, or at least muscle activation that would facilitate a forward trunk lean, is protective of the ACL [60, 61, 63, 67]. However, future studies are needed that incorporate electromyography of the core musculature to gain a better understanding how the core muscles might activate to better control the trunk, reduce knee loading, and prevent injury. With this information, more efficient and effect training programs may be developed that can be incorporated across large populations of athletes to alter knee loading in a positive way and potentially reduce ACL injury risk.

Critical Points

- Constraining the arms close to the body during a cutting maneuver increases knee loading patterns associated with ACL injury risk.
- Increased trunk angles away from the direction of cutting are associated with increased knee moments and may lead to increased ACL injury risk.
- Reducing trunk angles, medializing the center of mass, and shifting the center of mass anteriorly more over the foot are all associated with reduced knee moments and may lead to reduced ACL injury risk.
- Studies investigating the role of the core musculature using electromyography provide preliminary evidence of a connection between active and reactive activations of the core muscles and knee loading patterns relevant to ACL injury.

10.6 The Core-ACL Connection: Causation or Just Correlation?

Although the evidence from cross-sectional, epidemiological, and interventional studies previously discussed shows associations between measures of the core and contributors to ACL injury risk, they fall short of demonstrating that core stability alters ACL injury risk. Cross-sectional and epidemiological studies cannot establish causation, and previous interventional studies have lacked the systematic approach necessary to determine if the core-directed exercises are an essential part of the training programs or if they could be removed without reducing efficacy. Moreover, perhaps the most relevant question to answer for the at-risk athlete is whether, on an individual level, improving core stability can reduce knee loading and thereby reduce ACL injury risk. However, three interventional studies that focused narrowly on core stability interventions and outcomes shed some light on the direct role that core stability training may play in reducing ACL injury risk and provide direction for future investigations in this area.

Pedersen and colleagues [68] studied soccer participation as a novel way to elicit changes in trunk control, hypothesizing that unanticipated perturbations to the trunk due to repeated directional changes and other movements during soccer would improve trunk control. Previously inactive women were recruited and allocated to 16 weeks of either playing soccer, running, or continuing to not train (negative control). Before and after the week training period, displacement after sudden trunk loading was assessed for all participants. A weight attached to a pulley was dropped suddenly, providing an anterior tug on the trunk that the subject was asked to resist (Fig. 10.5). Members of the soccer group significantly reduced trunk displacement after sudden loading, indicating that this group improved their trunk control. In contrast, no significant change in trunk displacement was observed in either the running group or negative control group. To examine the differences between soccer and running in greater detail, nine players

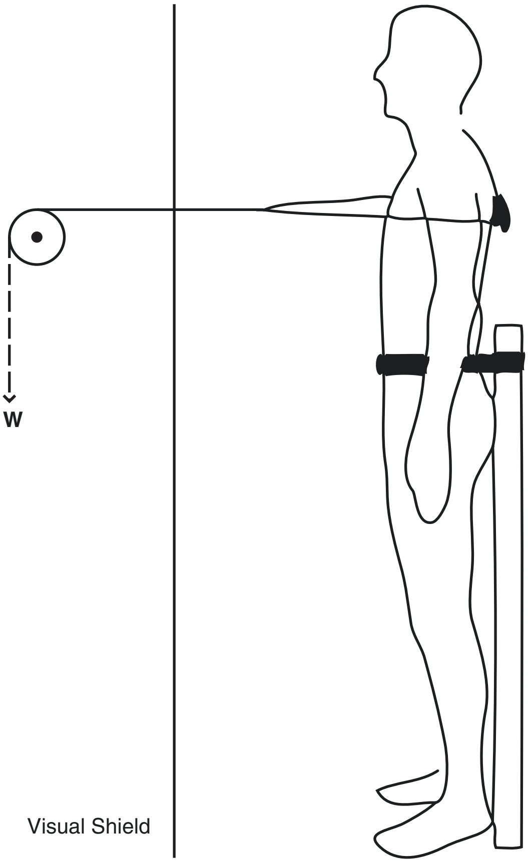

Fig. 10.5 Setup for generating a sudden forward pull to the upper part of the subject's trunk used by Pedersen et al. [68] to quantify trunk control. A cable is fastened to a rigid bar at the back by means of a harness attached to the upper part of the trunk. At a random time, an electromagnet is used to increase the weight W suddenly from 0.5 to 5.9 kg, creating an anterior tug on the torso. Movement of the trunk is measured by a potentiometer mounted on the pulley (Modified with permission from Pedersen et al. [68])

were filmed during three soccer training sessions to assess their movement patterns. Over these 27 hours of soccer training, the women made 191.5 ± 63.3 specific movements per hour on the field, including heading, dribbling, shoulder tackling, stopping, and turning. These movements present challenges to the core musculature over and above those required for the running control group, suggesting that sudden, unanticipated perturbations of the trunk may be important in eliciting changes in trunk control.

In a study aimed at determining if altering trunk control leads to altered knee loading and thereby altered ACL injury risk, Jamison and colleagues [23] analyzed the effectiveness of two different 6-week training programs (whole-body resistance program and trunk stabilization program). Both regimens included traditional, whole-body bilateral strength training exercises with free weights (such as bench press, deadlift, squats, lat pulldowns); however, the trunk stabilization program replaced one set of the traditional free weight exercises with trunk stabilization exercises. Peak external knee abduction moments (pEKAbM) during an unanticipated 45° cut and displacement after a sudden force release were assessed pre- and post-testing for 22 men who completed the training programs (11 per intervention group). Athletes completing the whole-body resistance training-only program significantly worsened their knee loading (pEKAbM during the cut) and worsened their trunk control (lateral trunk displacement following the sudden force release). The trunk stabilization group did not demonstrate any changes in these variables. The changes in the two programs were not significantly different from each other either, although the study was underpowered to prove this to be true. Nevertheless, the results suggest that the whole-body resistance training program's lack of any challenge to core stability negatively affected trunk control, which may have in turn negatively affected pEKAbM. While the trunk stabilization program was not able to improve trunk stabilization in this population, it is possible that the inclusion of the trunk stabilization exercises had a protective effect on trunk control, limiting any potential negative effects of the resistance training. The observed coupling of negative changes in trunk control and pEKAbM in the whole-body training group is consistent with the theory that the trunk may have an influence on knee loading that endangers the ACL, though this intriguing observation deserves further study.

A third study by Dempsey et al. [69] explored the effectiveness of whole-body cutting technique modification training in reducing pEKAbM and pTIRM during cutting maneuvers.

Nine male football, rugby, and soccer athletes completed a 6-week training program that focused specifically on reducing lateral reaching of the plant foot and decreasing lateral lean of the trunk away from the change of direction by providing immediate oral and visual feedback on cutting technique. Peak external knee abduction moments (pEKAbM) were estimated during a 45° unanticipated side-step cut before and after the task-specific training. Significant reductions in pEKAbM ($P = 0.034$), lateral trunk lean ($P = 0.005$), and lateral reaching of the plant foot ($P = 0.039$) were observed following training. While lateral trunk positioning and pEKAbM both improved, the simultaneous improvement in foot position makes it difficult to conclude whether it was the change in foot position or the change in trunk lean that led to the reduction in knee loading. In addition, no crossover tests were done in this study to determine whether improvements in the 45° cutting task carry over to other common high-risk activities. This study does demonstrate, however, that trunk positioning changes can be attained through task-specific training using visual and audio feedback, which may be useful when considering ACL rupture risk reduction training in the future.

In summary, soccer training, which by nature includes many sudden perturbations to the trunk, appears to be effective based on current reports in the literature in improving trunk control [68]. Running and static trunk stabilization exercises do not appear to improve trunk control, although they may assist in maintaining control [23, 68]. Eliminating core-directed exercises in whole-body resistance training appears to negatively influence trunk control and knee loading [23]. Lastly, task-specific side-step cutting training may improve cutting mechanics, including lateral trunk position and foot placement, as well as reduce adverse loading of the knee during the cut [69].

While these studies provide modest insight into the best ways to train the core and the connection between trunk control and ACL injury risk factors, further work is required in these areas to better understand this connection. Well designed, randomized control trials that mechanistically identify which components of exercise interventions are effective and efficient in triggering improvements in knee loading and reducing ACL injury incidence are critical to easing the challenge of identifying those at greatest risk of injury and those who would benefit the most from ACL injury prevention interventions. Emphasis should also be placed on reducing the burden of these interventions so that more athletes comply with and benefit from them. Moreover, most of the tests for core stability described in this chapter are only feasible to perform in the laboratory. More clinically feasible tests also need to be developed to assess core stability both for screening individuals at risk and determining which exercise interventions are most effective for the large prospective populations necessary for ACL injury incidence research.

Critical Points

- Soccer training, which incorporated many sudden, unanticipated trunk perturbations, was effective at improving trunk control.
- Whole-body resistance training alone (i.e., with no core training component) may have negative effects on both trunk control and knee loading which endangers the ACL.
- Task-specific cutting training can improve lateral trunk and foot positioning as well as reduce knee loading which endangers the ACL.
- More studies are needed to determine if core stability is a main factor in the ACL injury mechanism.
- Training programs targeted at improving core stability need to be clinically feasible in both scope and equipment.

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Proximal Risk Factors for ACL Injury: Role of the Hip Joint and Musculature

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Abstract

This chapter summarizes the role of the hip for potentially injurious knee loading and noncontact ACL injuries. Anatomical factors of the hip and knee are discussed with regard to their interdependence during functional activities. The influence of hip mechanics on knee potentially injurious knee loading during functional tasks is described. The biomechanical factors of the hip joint that are associated with stiff landing and cutting strategies (that contribute to greater knee loading) are described. Neuromuscular and muscular contributions to altered hip mechanics leading to ACL injuries are considered.

11.1 Introduction

The knee is often considered a victim of the hip. The knee serves as a link between the thigh and lower leg (shank) to the hip and ankle joints through what is termed the lower extremity kinetic chain. While anterior cruciate ligament (ACL) injury is the result of altered loading of the knee, the mechanism of loading cannot be considered in isolation because the mechanics at these joints are interdependent. When the foot is planted on the ground, neither movement nor loading of the knee can be examined without considering the ankle/foot complex or the proximal factors including the hip, pelvis, and upper body. This chapter will focus on the proximal risk factors for ACL injury, specifically the role of the hip in potentially injurious knee loading.

11.1.1 Anatomical Considerations of the Hip Joint

The hip joint is comprised of the articulation between the proximal femur and pelvis that allows for considerable motion in the sagittal, transverse, and frontal planes. It is considered the most stable joint in the body owing to its muscular support and boney congruency. The hip has important antigravity functions that support and propel the weight of the body during standing, walking, and running. It also serves as an axis through which the lower limb and upper body regulate the position of the center of mass for balance and postural control. Although 22 muscles cross the hip joint, the major hip extensor (gluteus maximus [GMAX]) and the major hip abductor (gluteus medius [GMED]) are consid-

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ered the most important antigravity muscles acting at the hip due to their location and force-generating capacity [1]. Additionally, their broad attachment sites allow them to function in multiple planes. The GMAX is the most powerful hip extensor. It has a large physiologic cross-sectional area and long muscle fibers that make it capable of producing considerable force through large excursions at high velocities [1]. As a result of its broad attachment to the pelvis, the GMAX also has the capacity to be a hip abductor and external rotator. The capacity for generating hip external rotation torque is greater at smaller degrees of hip flexion because the moment arm for external rotation decreases at greater hip flexion angles [2]. The GMED is the most powerful hip abductor. During single-limb stance, it works to stabilize the pelvis and limit hip adduction. Despite its smaller size, the GMED rivals the GMAX with respect to physiologic cross-sectional area due, in part, to its shorter muscle fiber lengths. The GMED is capable of producing substantial force much like the GMAX but operates through smaller excursions.

11.1.2 Anatomical Considerations at the Knee Joint

In contrast to the hip, the knee joint is considered much less stable as a result of its boney anatomy and supporting muscles. The knee joint affords considerable motion in the sagittal plane and substantially smaller degrees of motion in the transverse and frontal planes. The quadriceps muscles function much like the hip extensors in an antigravity role for shock absorption and support. The large physiologic cross-sectional areas of the quadriceps make them powerful knee extensors. The hamstrings have smaller cross-sectional areas and act at the knee and hip joint as flexors and extensors, respectively. These two muscle groups primarily cross anterior and posterior to the knee joint. Along with their roles in flexing and extending the knee, they contribute to the anterior and posterior stability of the tibiofemoral joint. The extent to which they contribute to anterior/posterior stability is dependent on sagittal plane knee angle. Forceful quadriceps contractions at smaller knee flexion angles contribute to anterior shear force at the proximal tibia, whereas hamstring contractions at larger knee flexion angles exert a posterior shear force [3]. Along with several other muscles crossing the knee, the quadriceps and hamstrings contribute to frontal plane motion and stability [4]; however, their effectiveness is limited by their relatively small moment arms in these planes. As a result, athletes rely more heavily on passive structures at the knee (i.e., the ACL) for stability in the frontal and transverse planes.

The potential influence of the hip on the knee seems intuitive when considering the juxtaposition of the joints with respect to function and stability. In particular, the greater available motion across planes at the hip joint contrasts with the limited range of motion and stability in the transverse and frontal planes of the knee. Not surprisingly, the hip is implicated in several acute and overuse injuries of the knee.

11.1.3 ACL Injury: Altered Knee Loading

ACL injuries occur when the load-bearing capacity of the ligament is exceeded. Although these loads can result from direct contact to the knee, ACL injury mechanisms that do not involve contact are of particular concern as their etiology is less clear. It has been reported that as many as 70% of ACL injuries occur as a result of noncontact mechanisms [5–7]. In these cases, a combination of altered knee positions and torques leads to increased loads in the ligament and ultimately failure. The question arises how does the hip contribute to these altered positions and torques?

Noncontact injuries generally occur during tasks that involve some form of deceleration and/or change of direction [5, 7]. The body of literature that describes the mechanics (i.e., hip joint positions and torques or moments) of proximal movement patterns during landing and cutting (change of direction) activities and their influence on knee loading is extensive. Movement requirements for landing and cutting differ as do the relationships between hip and knee mechanics during the performance of these athletic tasks. As such, the mechanics of proximal movement patterns and their influence on knee loading will be described separately for landing and cutting tasks.

The ACL's primary function is to resist internal tibial rotation and anterior tibial translation and is considered a secondary restraint to knee abduction. In vitro and modeling studies suggest that excessive knee abduction (valgus) [8] and tibial rotation [9], combined with large knee adductor moments (also referred to as knee valgus moment) [8, 10] and increased anterior shear force [11], result in increased and potentially injurious loads on the ACL. In particular, the ACL is considered more vulnerable to these loads when the knee is in extension or a small degree of flexion (0–40°) [8]. Increased anterior tibial shear force is thought to result from forceful quadriceps contractions at small knee flexion angles [12]. Moreover, cadaveric studies have shown that quadriceps pull increases loading on the ACL [8] and can rupture the ligament [11]. These mechanisms are consistent with injury mechanism described from videotape and questionnaire analyses that show noncontact ACL injuries occur when the knee is in relative extension, rotation, and valgus [7]. Although some authors have postulated that increased knee adductor (valgus) moments during a drop-landing task have a statistical relationship to ACL injury risk in female athletes [13], there is still controversy on this point. For example, Goetschius et al. [14] found no significant relationship between a high knee abduction moment (as determined by a clinic-based algorithm) and ACL injury in female athletes. Currently, anterior tibial force and frontal plane loading are considered the primary loading mechanisms responsible for noncontact ACL injuries.

Critical Points

- Owing to its anatomy and position in the kinetic chain, the knee is vulnerable to excessive frontal and transverse plane motions of the hip.
- Noncontact ACL injuries occur when the load-bearing capacity of the ligament is exceeded.
- Excessive loading is the result of altered knee positions, displacements, and torques.
- Mechanics thought to overload the ACL to failure involve excessive anterior tibial force induced by forceful quadriceps contraction and excessive knee valgus angles and torques.

11.2 Hip Mechanics Related to Altered Knee Loading

Proximal movement mechanics that limit engagement of the hip in the sagittal plane and rely more heavily on the frontal and transverse planes have potentially injurious influence on the knee. While this general pattern may look different during landing and change of direction tasks, these mechanics have the potential to increase loads on the ACL.

11.2.1 Landing Mechanics

An interdependence of the hip and knee joints in the frontal plane is easy to visualize and is often observed during an ACL injury. Video sequences of ACL injuries frequently depict a collapsing in of the knee with hip adduction. While it is not clear if this position is causing the ACL rupture or is a result of the instability following injury, it clearly depicts the relationship between hip adduction and knee valgus. Some authors [15] have noted that collapse into an overall valgus lower limb position is a result of hip internal rotation, knee valgus, and external tibial rotation. It is not surprising that hip and knee frontal plane angles are related during bilateral landing tasks. With the feet fixed on the ground, movement of the femurs toward each other in the frontal plane (hip adduction) results in knee valgus (abduction). Hip adduction angle is strongly correlated with knee valgus angle during a drop-landing task [16], and this posture during landing directs the vertical ground reaction forces lateral to the knee joint in the frontal place, resulting in knee adductor (valgus) moments (Fig. 11.1b) [17].

Biomechanics review: joint moments

Lower extremity joint moments are calculations of torques experienced at the joint derived from equations that consider the segments of the limb, the joint positions, and the location, magnitude, and direction of externally applied forces (i.e., GRF). Using these equations, moments may be calculated at each joint in the sagittal, frontal, and transverse planes. The relationship between the joints and the external force in a single plane can be illustrated by considering the joint center, or axis of rotation, and the ground reaction force vector (GRFV). Generally, GRFV represents the force an individual applies to the ground during weight bearing. The resultant GRF vector (rGRFV) represents the magnitude and the direction of that force with its origin at the COP. The COP is considered the point of application of the resultant GRF vector and is located in the foot. The location of the rGRFV with respect to the joint center dictates the direction of the joint moment. In general, the magnitude of the GRFV and the distance between the vector and the joint center (moment arm for GRF) dictate the magnitude of the external moment applied to the joint. This external moment must be resisted internally by a moment generated by muscles and soft tissues.
The description of moments in the literature varies; some authors report internal moments, while others report external moments. It is important to understand that they are equal and opposite, but the differences in reporting can cause confusion when interpreting the effect of the moment on the joint. For our purposes, we will refer to moments as internal or those that reflect the torque generated by muscles or soft tissues.
For example, an internal hip extensor moment refers to the torque generated by the hip extensors and surrounding soft tissues to counteract an external moment created by the rGRF and its moment arm. As seen in Fig. 11.1a, the rGRF (black arrow) is anterior to the hip joint center, a distance indicated by the dashed line (moment arm for GRF). In this case, the GRF is creating an external flexion moment that works to flex the hip. The hip extensors must act to counteract this moment by producing an equal and opposite moment referred to as an internal hip extensor moment (represented by the red arrow). These moments can increase if the GRF increases and/or the moment arm for the GRF increases.
This can be confusing when referring to the knee in the frontal plane. As seen in Fig. 11.1b, the rGRFs are lateral to the knee joint centers, creating an external moment that wants to abduct the knee, commonly referred to as an external knee valgus moment. These moments are also referred to as internal knee adductor moments, generated by the knee adductors and soft tissues to resist the external moment. Given that the knee has limited muscular support in the frontal plane, we assume that internal frontal plane moments are primarily generated by soft tissues. Note that in this example, the moment arm for the GRF is longer on the right compared to the left. This longer moment arm will contribute to a larger knee adductor moment on the right.

GRF ground reaction force, *GRFV* ground reaction force vector, *rGRFV* resultant GRF vector, *COP* center of pressure

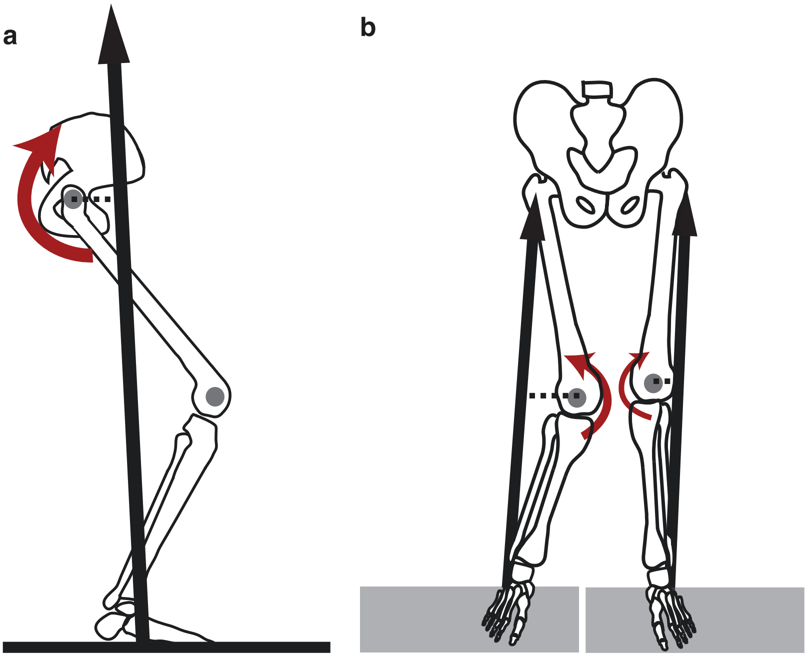

Fig. 11.1 (**a**) Sagittal and (**b**) frontal views of the lower extremity during a squat. *Black arrows* represent the resultant ground reaction force vector. *Dotted lines* represent the moment arm for the ground reaction force. *Red arrows* represent the internal joint moments

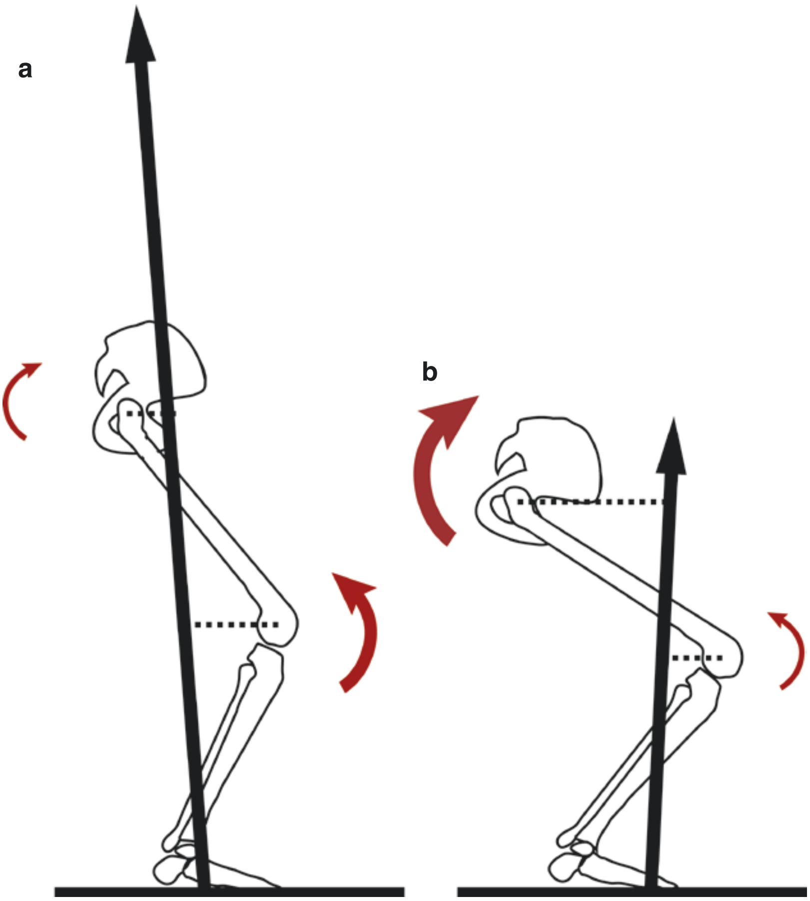

Fig. 11.2 (**a**) The influence of hip flexion on sagittal plane hip and knee moments during landing. Limited hip flexion during landing shifts the resultant ground reaction force vector (*black arrow*) posterior, closer to the hip joint center and farther from the knee joint center (*gray circles*). This decreases the lever arm (*dotted line*) for the vertical ground reaction force at the hip and increases it at the knee in the sagittal plane. This results in smaller hip and larger knee extensor moments (*red arrows*) and thereby an increased demand on the knee extensors to attenuate ground reaction forces. (**b**) In contrast, a landing strategy that includes greater hip flexion will shift the resultant ground reaction force vector forward closer to the knee joint center and further from the hip joint center. Compared to the strategy depicted in (**a**), this strategy results in a greater relative contribution from the hip extensor to attenuate ground reaction forces, thereby reducing the relative demand on the knee extensors

In addition to the easily visualized frontal plane interaction between hip and knee mechanics, the relationship between hip and knee mechanics in the sagittal also plays a role in potentially injurious mechanics. A more erect sagittal plane shock absorption strategy during landing reflects a biomechanical pattern that places greater mechanical loads on the knee joint in both the sagittal and frontal planes. This strategy is often referred to as a “stiff landing” versus a “soft landing” that involves a more sagittal plane flexion. Stiff landing strategies are typically characterized during bilateral drop-jump landings but can also apply across double-limb and single-limb tasks such as bilateral jumping, single-limb landing, and hopping. The mechanics associated with stiff landing strategies increase the demands at the knee in both the sagittal and frontal planes [18].

The biomechanical factors associated with stiff landing strategies that contribute to greater knee loading are illustrated in Fig. 11.2. Stiff landing strategies involve smaller degrees of hip and knee flexion that result in greater vertical ground reaction forces [19] compared with soft landing. Reduced lower extremity excursions along with larger ground reaction forces lead to increased loading rates and decreased shock attenuation. In addition, limited hip flexion results in a more erect trunk posture that shifts the center of mass and the application of the ground reaction force (COP) posterior. This increases the lever arm for the vertical ground reaction force at the knee in the sagittal plane and, in turn, increases the intersegmental forces acting to flex the knee (Fig. 11.2a). Larger intersegmental forces combined with a larger ground reaction force result in an increased demand on the knee extensors to attenuate the ground reaction forces. In contrast, greater hip flexion (Fig. 11.2b) positions the trunk more anteriorly, shifting the ground reaction force vector closer to the knee joint center and farther from the hip joint center. This increases the lever arm for the vertical ground reaction force at the hip and decreases the lever arm for the knee in the sagittal plane. As a result, the demand on the hip extensors to attenuate the ground reaction forces is increased, and the demand on the knee extensors is decreased. This allows for a strategy that attenuates impact forces with a more equal utilization of the knee and hip extensors. A more even distribution coupled with a smaller magnitude ground reaction force ultimately decreases the relative demand on the knee extensors and reduces the anterior tibial shear force.

This is illustrated in a study that performed a comparison between groups that used a stiff or soft strategy during a bilateral drop jump from a height of 36 cm [20]. Athletes that used a soft strategy flexed their hips and knees on average 100° and 90°, respectively, while those that used a stiff strategy limited their hip and knee flexion to an average of 87° and 67°, respectively. When considering the contribution from the hip and knee extensor to shock attenuation, a considerable difference in knee-to-hip extensor moment ratio was observed between the strategies. The stiff landing strategy resulted in a 66% larger ratio, indicating substantially greater contributions from the knee extensors than the hip extensors to attenuate impact forces. This resulted in 10% greater average knee extensor moments and 35% greater quadriceps activation during deceleration. Smaller knee-to-hip extensor moment ratios observed with soft landing strategies reflect a shift in demand away from the knee to the hip.

An increased demand on the knee extensors is of particular concern with respect to injury risk. As mentioned above, large quadriceps forces can contribute to anterior tibial shear forces and increased loading of the ACL [11]. Increased anterior tibial shear forces have been noted in individuals who perform a drop-landing task with less hip flexion and greater knee flexion motion and greater knee extensor moments and quadriceps activation [21]. After accounting for the effects of gender, these variables combine to explain 57% of the variance in anterior shear force during a drop-landing task.

While Fig. 11.2 illustrates potential biomechanical effects of hip flexion angle on sagittal plane knee loading during landing, it represents an oversimplification of a dynamic task. In this figure, only one potential combination of hip and knee flexion angles is considered at a single point in time. It is important to understand that motion of the hip and knee and coordination between the joints throughout the task is important. Greater hip flexion angular velocity at initial contact of a stop jump is associated with reduced posterior and vertical ground reaction forces. It is not merely a position of hip and knee flexion but active hip and knee flexion throughout landing that reduces impact forces during deceleration [12]. Furthermore, coordination of hip and knee flexion is also important. It has been proposed that if the hip flexes more slowly than the knee during deceleration, the tibia will undergo greater anterior translation, resulting in an increase on the load on the ACL in the absence of appropriate muscular control [22]. This is of concern because the synchronization of hip and knee flexion is not always possible during athletic competition when positioning the trunk anteriorly to allow for hip flexion, which is difficult or ineffective.

In addition to increasing knee extensor demands, stiff landing strategies also play a role in frontal plane knee mechanics. Greater frontal plane loading of the knee is observed during landings that employ a stiff landing strategy. Knee adductor (valgus) moments were 2.2 times greater in a group of athletes who limited their hip and knee flexion during landing compared with those who used a “soft” landing strategy [20]. As illustrated in Fig. 11.3, the athlete that

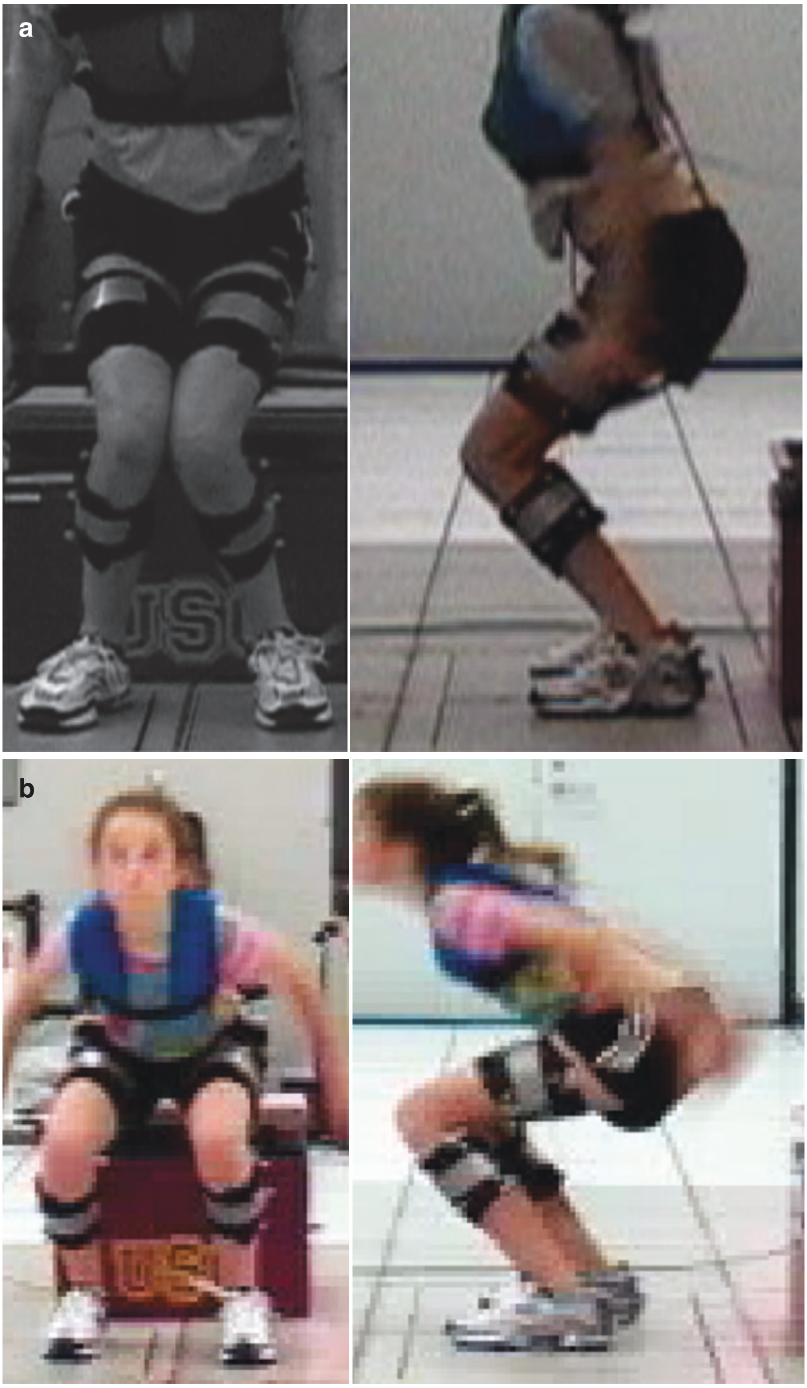

Fig. 11.3 Sagittal and frontal plane kinematics associated with a "stiff" (**a**) and "soft" (**b**) landing strategy. The athlete using a "stiff" landing strategy with less hip and knee flexion also exhibits greater knee abduction (**a**), whereas the athlete that is flexing through the hips and knees maintains a more neutral frontal plane position at the knee (**b**) (Reprinted with permission from Pollard et al. [20])

limits hip and knee flexion during landing exhibits greater apparent knee abduction (valgus) (Fig. 11.3a), whereas the athlete that flexes through the hips and knees maintains a more neutral knee position (Fig. 11.3b). Decreased engagement of the hip extensors, indicated by larger knee-to-hip extensor moment ratios, combined with greater knee frontal plane loading in the stiff landing group suggests that hip extensors may be important for lower extremity control outside the sagittal plane as well. The higher knee adductor (valgus) moments are representative of a strategy aimed at attenuating impact forces that should ideally be absorbed at the hip. The combined finding of diminished use of the hip extensors and higher knee adductor (valgus) moments reflects a landing strategy that relies more on the frontal plane to attenuate impact forces that should ideally be absorbed by the sagittal plane hip musculature. Given its capacity to function as a hip abductor and external rotator, engaging the gluteus maximus during landing may be important for reducing frontal plane loading of the knee.

An understanding of the relationship between the hip and knee during bilateral jumping landing tasks allows for the use of such tasks for screening of movement-related risk factors. Specific criteria related to observations of sagittal and frontal plane joint angles have been established for risk screening during bilateral landing tasks, including sagittal plane hip and knee angles and range of motion, as well as frontal plane knee position (see also Chap. 16) [23]. A two-dimensional measurement of the minimum distance between the knees provides information regarding knee valgus angle during a drop-landing and vertical jump tasks. This measure is strongly related to hip adduction angle during a drop land [16]. The value in using these measures was highlighted by a prospective study that found postpubertal female athletes who scored the lowest percentile for knee separation distance had a 3.62-fold increase in risk for knee injuries. These findings support the relationship between excessive hip adduction during bilateral landing mechanics that increase risk for injury [24].

Critical Points

- Hip adduction is related to knee abduction (valgus) and adductor (valgus) loading double-limb landing.
- Soft landing strategies that include increased hip flexion during landing engage the hip extensors and decrease the demand on the knee extensors to attenuate impact forces.
- Knee abduction (valgus) and adductor (valgus) loading is reduced during soft landing.
- Given its capacity to function as a hip abductor and external rotator, engaging the gluteus maximus during landing may also be important to reduce frontal plane knee loading.

11.2.2 Cutting Mechanics

Hip mechanics are related to frontal plane knee loading during athletic cutting or change of direction tasks; however, the relationship is different than that described during double-limb landing. During landing, hip adduction and internal rotation are associated with increased knee frontal plane loading. In contrast, it appears that hip abduction and internal rotation contribute to increased knee frontal plane loading during cutting [25–27]. This is true for cutting tasks that involve a change in direction away from the stance limb (side-step cutting). The different demands placed on the hip with respect to mobility and regulation of the upper body during cutting compared with landing underlie the contrasting relationship between the hip and knee in each task. During landing, trunk and hip flexion work to decelerate the falling body and absorb vertical ground reaction forces. Hip adduction and internal rotation combine to create a collapsing of the lower extremity that increases knee valgus loading in this task (Fig. 11.1b). In contrast, cutting requires horizontal deceleration of the forward progression of the body, along with redirection and translation into the new direction [28]. Cutting to larger angles imposes greater deceleration and translation demands than those performed to smaller angles, and these subcomponents are accomplished using different lower extremity and trunk mechanics [28]. During cutting, instead of potentially collapsing in, the hip is acting in the frontal plane (abducting and externally rotating) to redirect and translate the body in a different direction. Therefore, the effects of hip mechanics on knee loading must be considered differently during cutting.

During side-step cutting, knee adductor (valgus) moments are associated with hip abduction, hip internal rotation, and an internally rotated foot position at initial contact (Fig. 11.4) [27].

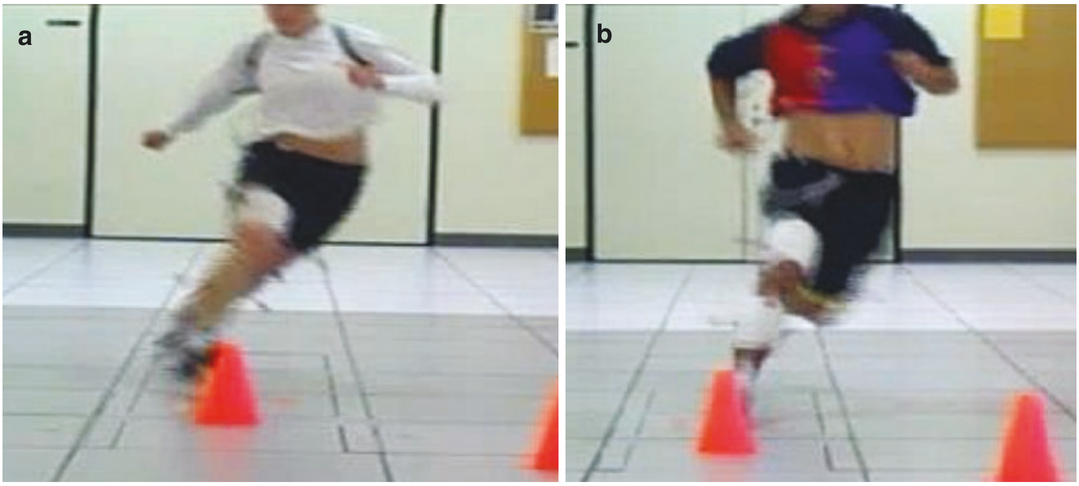

Fig. 11.4 Hip mechanics associated with knee adductor (valgus) moments during cutting. When compared to the athlete in (**b**), the athlete in (**a**) positioned their limb laterally so that the hip is in greater abduction, and internal rotation, with a more internally rotated foot position. This strategy limits the demand on the hip abductors. Along with a more laterally directed ground reaction force, these factors correlate with greater knee adductor (valgus) moments (Reprinted with permission from Pollard et al. [18])

Increasing the step width or positioning the stance limb foot more lateral to the body by abducting the hip away from the direction of the turn (Fig. 11.4a) results in larger knee adductor (valgus) moments [25, 29]. Compared with running, peak knee adductor (valgus) moments increase almost fourfold during cutting tasks performed with a larger step width (~60 cm) [25]. Even small increases in step width (~15 cm) have been reported to result in a 37% increase in knee moments compared with cutting performed with no step width alterations [29]. This relationship does not hold true for side-step cuts performed to larger angles (90° and 110°). While larger lateral ground reaction forces are necessary for performing cuts to larger angles, hip abduction is not related to knee frontal plane loading when changing direction to larger angles [30, 31].

Greater hip abduction contributes to increased knee adductor (valgus) moments by altering the relationship between the body's center of mass (COM) and the center of pressure (COP). Greater abduction moves the foot and center of pressure more lateral to the center of mass, creating a larger lever arm for the vertical ground reaction force (GRF) in the frontal plane (Fig. 11.5). This increases the intersegment forces that contribute to the knee adductor (valgus) moment about the knee joint. Furthermore, the initial impact of the abducted limb coming in contact with the surface creates a larger laterally directed GRF. It is not surprising that a strong association exists between peak lateral GRF and peak knee adductor (valgus) moment during cutting [27]. The lateral GRF imposes a large laterally directed intersegmental force to the distal end of the tibia, further increasing the knee adductor (valgus) moment. While this example illustrates the effect of changing the relationship between the COM and COP, it considers the effect of changing the hip position only. It is important to remember that the hip works to coordinate the lower limb and upper body for movement, support, balance, and orientation. Alterations in the COM-COP relationship that affect knee joint loading can also result from adjustments in trunk position with no changes in hip position [29].

In addition to hip abduction, hip and limb internal rotation are also associated with increase frontal plane loading of the knee during cutting. Sigward and Powers [27] found that when compared with female athletes with smaller knee adductor (valgus) moments, athletes with larger moments adopted a strategy that included twice as much hip internal rotation and a more internally

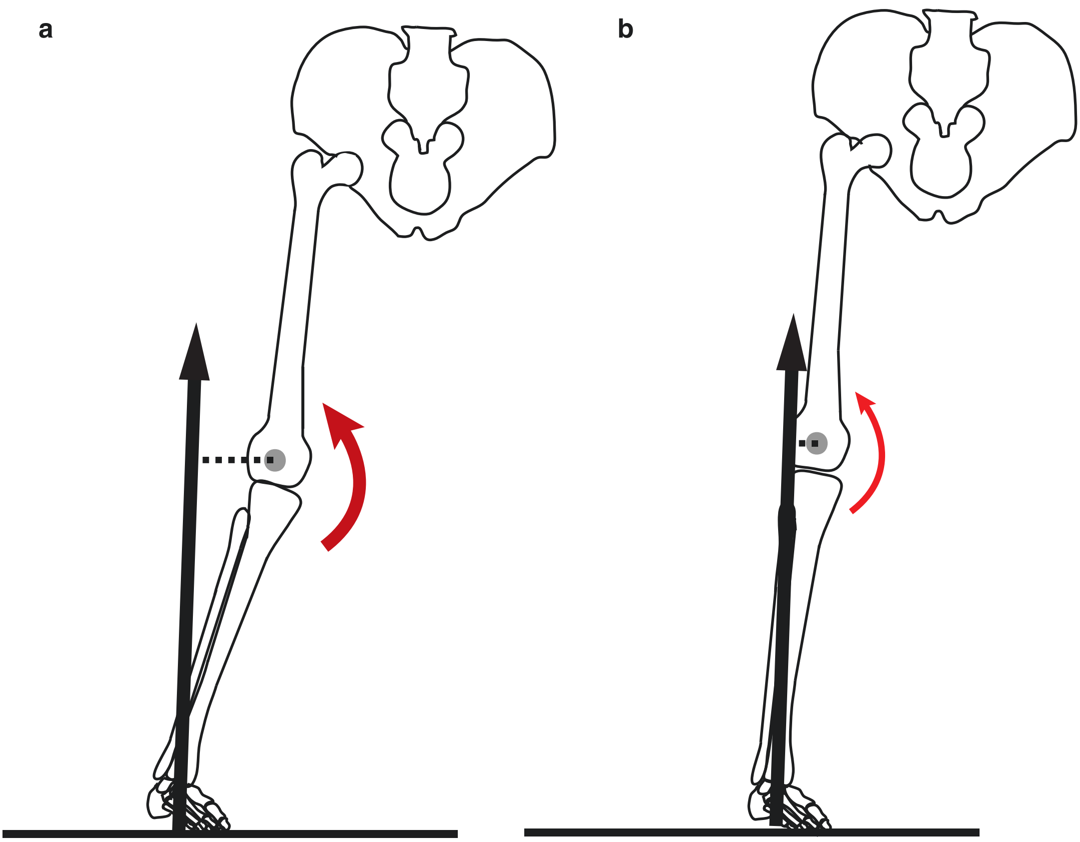

Fig. 11.5 The contribution of hip abduction to knee adductor (valgus) moments during cutting. Increased hip abduction (**a**) moves the center of pressure (located in the foot) laterally with respect to the center of mass (*gray circles*), creating a larger moment arm (*dotted line*) for the vertical ground reaction force (*black arrows*) at the knee in the frontal plane. The larger lever arm will result in greater intersegmental forces acting to abduct the knee and a larger knee adductor (valgus) moment (*red arrows*). Knee adductor (valgus) moments are decreased for a given vertical ground force when the hip is adducted, bringing the center of pressure closer to the center of mass and reducing the moment arm (**b**)

rotated foot during a 45° side-step cut. Hip internal rotation correlated with increased knee adductor (valgus) moments [27]. Unlike hip abduction, the relationship between hip internal rotation and knee adductor moments has also been observed across several studies and during cutting performed to larger angles (90° and 110°) [30, 31]. Individuals with larger knee frontal plane loading during cutting appear to contact the ground with their limb rotated in the direction of the turn (Fig. 11.4).

Similar to landing, it appears that cutting strategies that increase the risk for ACL injury through frontal plane loading are those that rely more heavily on frontal and transverse plane mechanics. It is not clear why individuals adopt such strategies or how they relate to engagement of the hip in the sagittal plane during cutting. Hip internal rotation during landing and cutting may increase frontal plane loading of the knee. However, when considering the hip in the frontal plane, excessive hip adduction during landing, but abduction during cutting, will increase frontal plane loading of the knee.

Critical Points

- Biomechanics at the hip are related to knee loading, and the relationship varies based on the demands of the task:
  - A more laterally placed foot and hip adduction increases frontal plane loading during cuts performed to small angle (45°), but not to larger angle (90° and 110°).
  - Greater hip internal rotation increases knee adductor (valgus) moments during cuts performed to smaller and larger angles

11.3 Neuromuscular Contributors to Altered Hip Mechanics

It is not only important to recognize injurious movement mechanics but also to understand factors that underlie them. In the previous section, the influence of the hip mechanics was discussed on potentially injurious joint knee loading. Patterns were described that limit engagement in the sagittal plane and rely more heavily on the frontal and transverse planes. In this section, factors related to the control of these strategies will be addressed. Specifically, the question of why would an athlete adopt a strategy that includes poor or potentially injurious lower extremity mechanics during athletic tasks is asked. Two potential answers to this question will be considered. First, the strategy is the consequence of an imbalance between the demands of the task and the athlete's capabilities (i.e., inadequate strength). Second, the strategy is a learned pattern that the athlete has adopted over time (i.e., alter control strategies).

11.3.1 Relationship Between Hip Strength and Knee Pathology

An athlete may adopt a strategy that includes poor or potentially injurious lower extremity mechanics during athletic tasks if they do not possess the appropriate strength or power needed to complete the task. Adequate strength is required to propel and control the body during dynamic movements such as landing and rapid change in direction tasks. While poor strength often results in poor athletic performance, it is also thought to be an important factor in injury risk. In the absence of appropriate strength, an athlete may adopt compensatory strategies to complete the task. These strategies may result in abnormal loading at adjacent joints.

Studies linking hip weakness and knee pathology provide some support for a potential relationship between hip muscle function and knee injury. Several studies have related hip weakness to lower extremity injuries [32–35]. Individuals diagnosed with iliotibial band syndrome [32], patellofemoral pain [33, 36], and lower extremity overuse injuries related to running [35] were found to have ipsilateral deficits in hip strength. Similar to ACL injury mechanics, altered hip control underlies the pathomechanics involved in these lower extremity injuries [37]. While a cause and effect relationship between hip strength and lower extremity injury cannot be assumed based on these data, a prospective study provided some evidence to support this link. Leetun and colleagues [34] evaluated hip strength in 140 male and female collegiate athletes prior to their sports season. Those athletes who sustained a lower extremity injury (to the back, hip, thigh, knee, foot, or ankle) during the season were found to have decreased hip abductor and external rotator strength compared with those who were not injured. In a recent large prospective study involving 468 athletes, 6 women and 5 men sustained noncontact ACL injuries [38]. Preseason testing determined that impaired isometric hip external rotation strength was associated with future injury risk (odds ration = 1.23, $P = 0.001$), as was decreased hip abduction strength (odds ratio = 1.12, $P = 0.001$).

11.3.2 Hip Strength and Knee Mechanics

While data suggest that a link exists between hip strength and knee injury, data regarding the relationship between hip weakness and knee mechanics provides some insight into how they are related. Frontal plane hip strength is thought to be important for stabilization of the pelvis. During unilateral stance, the stance limb hip abductors work to stabilize a level pelvis on the femur against the force of gravity. Hip abductor weakness is thought to result in the inability to maintain pelvifemoral control, manifested as excessive hip adduction and/or internal rotation or contralateral pelvic drop (Fig. 11.6). In addition, compensatory trunk lean over the stance limb is also thought to reduce the demand on the

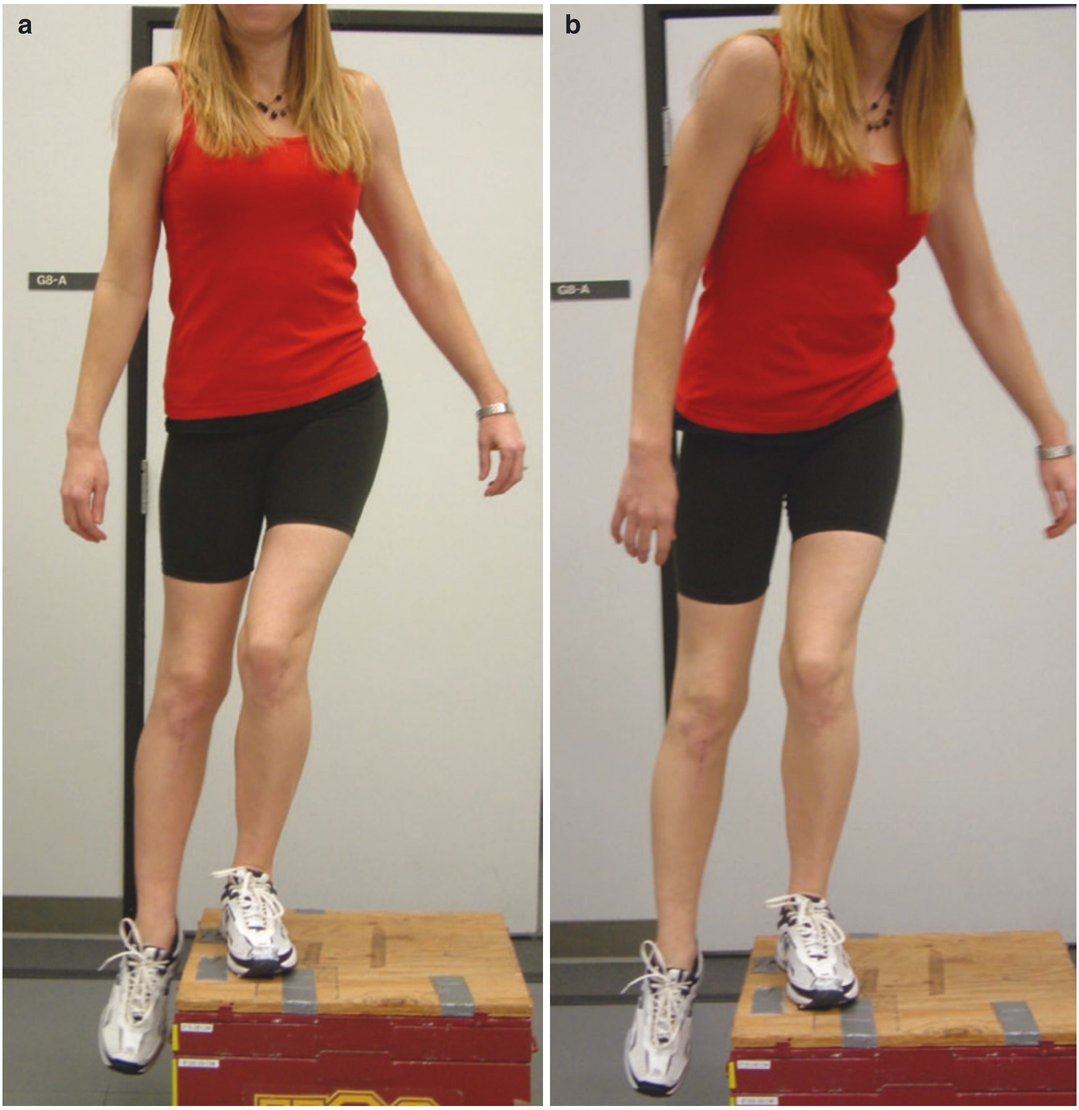

Fig. 11.6 Poor pelvifemoral control attributed to hip abductor weakness. (**a**) An individual with poor hip abductor function can exhibit excessive hip adduction, internal rotation, and contralateral pelvic drop. (**b**) Medial collapse of the femur is not as apparent if the individual compensates for hip abductor weakness by leaning the trunk over the stance limb

hip abductors. These compensations are related to hip abductor strength. Specifically, decreased eccentric hip abductor strength is related to greater femur adduction and internal rotation during a single-leg squat in females (see also Chap. 13) [39]. These results were supported by a clinical study conducted by Crossley and colleagues [40] who found that observational assessments of limb and trunk posture were related to hip isometric hip abductor strength. Good performance was based on the absence of trunk deviations and medial knee deviations along with a level pelvis and a neutral hip position in the transverse and frontal planes during a single-limb stepdown. Those whose performance was rated poor had a 29% decrease in hip abductor strength compared to those who were rated good. These data suggest that observational analysis of compensatory patterns may be an appropriate way to screen for hip abductor weakness.

Poor hip muscle function is also related to increased knee frontal plane motion. Associations between hip abductor and external rotator strength and knee valgus are observed during the single-limb squat test [39, 41]. Moreover, a moderate relationship was noted between knee valgus and hip abductor strength during a landing task, suggesting that hip abductor strength may be important for controlling hip adduction during double-limb tasks as well [42]. More recently, Stickler et al. [43] examined the relationship between frontal plane kinematics of a single-leg squat and hip strength. These authors found that hip abductor strength was a strong predictor of frontal plane projection angle. While relationships between strength and lower extremity mechanics have been noted in several studies, they are often small and inconsistent [44, 45]. A large study evaluating 2753 cadets reported that while hip external rotator strength was related to poor landing mechanics, it only had minimal influence [44]. Other studies failed to find similar relationships [45]. For example, Nilstad et al. [46] reported that hip abductor strength was not associated with frontal plane knee valgus angles during a drop-landing task in 279 Norwegian elite female soccer players.

While it is intuitive to consider hip muscle weakness a risk factor for ACL injury, experimentally the connection between hip strength and injury and knee mechanics continues to be inconsistent. This may be due to the manner in which strength is tested. More comprehensive measures of muscle function may reveal more robust relationships [47]. The majority of studies related to hip strength and ACL injury risk have examined maximal strength. However, Souza and Powers [47] examined hip muscle endurance and found that hip extension endurance was a predictor of hip internal rotation during running. Additionally, despite that fact that individuals with weaker hip abductors and external rotators performed a landing task with similar hip and knee kinematics, Homan and colleagues [48] found that the weaker individuals exhibited greater gluteal muscle activity than the strong individuals. The need for greater gluteal activity to achieve the same kinematics may precipitate earlier fatigue. Perhaps individuals who fatigue more quickly reach a state of reduced muscle strength during physical activities that is not captured with maximal strength tests in a non-fatigued state. Taken together, these studies suggest muscle endurance may be as important for hip mechanics as maximal torque producing capabilities.

The importance of adequate hip muscle function is underscored by improvements in landing mechanics following comprehensive hip specific training. For example, a 4 week supervised progressive training program, 3 times a week for 20–30 min, that included plyometrics and balance training on a BOSU (BOSU, Canton, OH) resulted in increased hip abductor and hip extensor strength and reduced knee valgus angles and moments during landing [49]. While muscle hypertrophy would not be expected on 4 weeks changes in hip strength and function indicate that improvements in hip muscle performance can improved hip and knee mechanics during landing.

11.3.3 Muscle Control Strategies

An athlete may adopt a strategy that includes poor or potentially injurious lower extremity mechanics during athletic tasks if the strategy is a learned pattern that the athlete has adopted over time. There is evidence to suggest that the manner in which an individual engages their muscles may also be a factor to consider and that not all poor mechanics should be attributed to the inability to generate enough strength or power. Mizner et al. [50] illustrated this concept by showing that available strength did not dictate lower extremity mechanics during a double-limb drop vertical jump. These investigators found that muscle strength was not predictive of the ability to improve landing technique. Athletes who exhibited lower extremity muscle weakness were able to improve their mechanics (i.e., decrease vertical ground reaction forces, knee valgus, and knee adductor [valgus] moments and increase knee flexion angle) after receiving simple instructions on proper landing technique. This suggests that the pattern observed before instruction was given may have represented a learned motor pattern, and not the inability to meet the demands of the task.

There is some evidence to support the notion that hip muscle activation contributes to lower extremity movement patterns. One study found an association between gluteal muscle activation timing (onset) and hip adduction and internal rotation excursion in women with patellofemoral joint pain during running [51]. Greater joint excursions correlated with later muscle onset. A similar relationship was noted in asymptomatic individuals during a single-leg squat [40]. Individuals rated as good based on trunk and pelvic posture, as well as hip and knee posture, had significantly earlier gluteus medius activation onset times. Together these relationships suggest that appropriate engagement of the gluteals during dynamic tasks is important. This concept is not novel, as many rehabilitation programs include neuromuscular training that emphasizes technique and control during functional exercises. It is important to remember that, as with strength, the associations between hip muscle activation timing and hip mechanics are also relatively weak, suggesting that it may be an important combination of the two that will improve lower extremity mechanics.

Critical Points

- Women exhibit decreased hip abductor, external rotator, and extensor strength when compared to men.
- Poor hip muscle function has been related to femur adduction and internal rotation.
- The ability to engage the hip muscles during dynamic activities may play a role in hip mechanics.
- The independent relationships between strength and muscle activation and hip mechanics during dynamic tasks are relatively weak suggesting that it may be important to consider both factors during training.

11.4 Overall Summary: Implications for Training

An understanding of biomechanical and neuromuscular risk factors for injury is needed for the development of effective injury prevention programs. Evidence supports strong consideration of the influence of proximal factors on injurious knee loading. In general, it appears that strategies that encourage sagittal plane motion and avoid excessive motion in the transverse and frontal planes at the hip decrease loading at the knee. Therefore, training should emphasize engaging the larger hip extensor muscles for power generation and using hip abductors and external rotators to stabilize frontal and transverse plane motion. Support for this strategy comes from studies that have evaluated tasks performed primarily in the sagittal plane and should be applied to exercises accordingly. However, it appears that the concept of limiting frontal and transverse plane motion applies only in part to cutting. Evidence suggests that limiting frontal and transverse plane motion during deceleration may reduce knee frontal plane loading but is likely important for redirecting and accelerating the body into the new direction. Therefore, application of these general principles to agility training should be done with caution. It is unlikely that an athlete will adopt a strategy that is ineffective or inefficient.

It is important to recognize that what is known with respect to altered hip mechanics and knee joint loading comes primarily from studies that evaluated pre-planned tasks performed in controlled environments. While these experimental designs do not represent the majority of events that an athlete will be exposed to in their sport, they do provide valuable insight into lower extremity risk factors for injury. There should be some concern if an athlete chooses to adopt altered movement strategies when performing these tasks because they are not likely to adopt good mechanics during more complex tasks encountered on the court or field. Therefore, training which emphasizes good mechanics during controlled exercises should be the first priority. This is usually accomplished using plyometric jumping and landing tasks. However, the transverse and frontal plane demands of athletic tasks must not be neglected. Transverse and frontal plane muscle groups will not only be called upon to stabilize motion but also to contribute to motion during tasks that do not occur primarily in the sagittal plane (i.e., cutting).

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12 Recovery of Hip Muscle Strength After ACL Injury and Reconstruction: Implications for Reducing the Risk of Reinjury

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Abstract

Recovery of lower extremity muscular strength and neuromuscular control are two of the most vital aspects of anterior cruciate ligament (ACL) rehabilitation, as well as efforts to prevent noncontact ACL injury. There is strong evidence regarding the association between decreased hip range of motion, particularly internal and external rotation, and noncontact ACL injury. Given that females are at greater risk for ACL injury compared with males, increased emphasis has been placed on identifying risk factors in the hip as well as throughout the kinetic chain for this injury. In this chapter, we discuss the relationship between hip and knee injury patterns and its implications for ACL reconstruction and rehabilitation and noncontact ACL injury prevention efforts.

12.1 Introduction

An anterior cruciate ligament (ACL) injury can be a debilitating entity, not only due to the lack of reestablishment of normal knee biomechanics in some cases, but also because of the muscular imbalance produced after ligament reconstruction. A staged and customized muscle rehabilitation program can be tailored to allow the patient to return to their activities in a timely fashion and diminish the risks of an ACL reinjury.

Identification of muscular deficits after an ACL injury is vital to prevent further injuries. In this regard, Petersen et al. [1] reported in a recent systematic review of 45 articles that all studies identified strength deficits after ACL reconstruction compared with control subjects. Of note, some of these deficits persisted up to 5 years after surgery depending on the rehabilitation protocol instituted. Knee flexion strength was more impaired with hamstring grafts and quadriceps strength was more impaired after bone–patellar tendon–bone ACL reconstruction. These authors suggested that muscular strength testing is important to determine if an athlete can return to competitive sports after an ACL reconstruction.

Female athletes are a specific population at increased risk for both primary and secondary ACL injuries. Prodromos et al. conducted a meta-analysis of 33 articles and reported that the mean ACL injury rate for females was significantly greater than males in basketball, (0.28 and 0.08 per 1000 exposures, respectively, $P < 0.0001$), soccer (0.32

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and 0.12 per 1000 exposures, respectively, $P < 0.0001$), and handball (0.56 and 0.11 per 1000 exposures, respectively, $P < 0.0001$) [2]. Such injury rates have resulted in a growing body of literature focused on the treatment of these injuries in addition to identifying risk factors and prevention programs [3]. Several studies have reported a reduction in the number of ACL tears after implanting a preseason neuromuscular training program [3–5]. Furthermore, studies have reported altered landing biomechanics in female athletes before and after ACL injury. The observed abnormal knee kinematics are associated with abnormal hip strength and movements [6]. Because of this, increased attention has been directed toward identifying the optimal balance of hip and knee motion in the female athlete, with the aim of preventing or reducing the rate of female ACL injuries.

For the abovementioned reasons, the purpose of this chapter is to describe important facts regarding the recovery of muscle strength after ACL reconstructions in female athletes and to outline the current interventions to diminish the risk of ACL reinjury. Combined lower limb biomechanics, pathogenesis, and prevention strategies will be presented.

12.2 Interaction Between Altered Hip Mechanics and Knee Injury Patterns

In the United States, approximately 200,000 ACL injuries per year are reported, resulting in an expense of billions of dollars for the health system [7]. Importantly, one of the most common causes of osteoarthritis (OA), but often overlooked, is the development of post-traumatic osteoarthritis after ACL tears in the young and active population [8, 9]. For these reasons, prevention and identification of risk factors for ACL tears are key to prevent the cascade of joint degenerative process. Importantly, female athletes are at an increased risk of injury. Potential explanations for this include increased knee valgus or abduction moments, generalized joint laxity [10], genu recurvatum [11], a comparatively smaller ACL [12], and the hormonal effects of estrogen on the ACL [13].

Although many risk factors have been identified such as age, sex, anthropometric measures, and psychological and inherent anatomical factors [3], limited evidence exists regarding the relationship between the range of motion of the hip (which acts as a "buffer" in forced rotation of the knee) in patients with an ACL injury. In this regard, available literature suggests an association between decreased hip motion in patients with ACL injuries, predominantly with decreased internal rotation of the hip. This suggests that an ACL injury may not only have an intrinsic knee etiology but can also be related to an adjacent joint-based problem [14–17].

Tainaka et al. [18] reported the possibility of an association between noncontact ACL injuries in high school athletes and hip range of motion. These investigators found that the incidence of ACL injury increased as hip internal rotation (IR) or external rotation (ER) decreased. However, the odds ratios were small and no other potential risk factors were included in the analysis. As previously reported, a restricted IR of the hip is in most cases associated with abnormal proximal femoral or acetabular anatomy [19] and has been correlated with ACL ruptures and reruptures in soccer players [20, 21] and in professional American football athletes [22].

Both femoral (decreased femoral head–neck offset or increased alpha angle) and acetabular (decreased center-edge angle [CEA]) bone deformities can place the ACL at risk [15, 23]. Yamazaki et al. [23] reported that the CEA of the ACL-injured patients group was significantly smaller than that of a control group, suggesting that ACL-injured patients may have a higher prevalence of acetabular dysplasia. Philippon et al. [15] reported that patients with a decreased femoral head–neck offset (alpha angle >60°) were at increased risk of having an ACL injury because of altered lower limb biomechanics. This increased risk was evident in both males and females, with a slight predominance in males. The ACL injury cohort had a mean alpha angle of 86° and 79° in males and females, respectively, the values of which are markedly higher than previously reported limits of normal alpha angles.

Beaulieu et al. [24] performed a simulated single-leg pivot landing study to assess the peak relative strain of the anteromedial bundle of the ACL in relation to the available range of internal femoral rotation. In their statistical model, peak ACL relative strain increased by 1.3% with every

10° decrease in femoral rotation. From this concept, these authors suggested that an athlete presenting with femoral acetabular impingement (FAI) with a 10° deficiency in internal femoral rotation would experience 20% more peak ACL strain during landing than a healthy athlete. Importantly, patients with abnormally elevated alpha angles may have diminished capacity at the hip to accommodate overall lower extremity internal rotation moments, potentially predisposing the knee (and other intra-articular structures) to a greater rotational stress. In this regard, Girard et al. [25] suggested that improving the femoral head–neck offset could result in an improved range of motion in the hip, specifically in flexion, thereby allowing knee forces to be normalized.

Given that females are at greater risk for ACL injury, increased emphasis has been placed on identifying risk factors throughout the kinetic chain for ACL injuries in female patients. In this regard, Imwalle et al. [26] studied lower extremity kinematics during 45° and 90° cutting movements and examined the amount of hip and knee internal rotation during each movement. Mean hip and knee internal rotation, in addition to hip flexion, were greater during the 90° cutting motion in female athletes. These authors concluded that increased knee abduction in female athletes was secondary to abnormal coronal plane motion of the hip. They proposed that neuromuscular training of the trunk and hips may be able to reduce ACL injury by improving extremity alignment. Similar findings were reported by Leetun et al. [27] who demonstrated athletes with greater hip abduction strength were significantly less likely to sustain a lower extremity injury. It has also been reported that adolescent males experience an equal hip abduction strength increase relative to their developing body mass, while their female counterparts have less hip abduction in relation to their developing body mass [28]. The lack of hip abduction strength in adolescent girls may be related to the elevated risk of ACL injury observed in adolescent females [6, 28]. Taken together, these findings demonstrate the need for young athletes, in particular young female athletes, to perform hip abduction strengthening exercises prior to high-level competition. Moreover, young female athletes should begin these strength training protocols around age 13, when their body mass grows disproportionally to their hip abduction strength.

Critical Points

- Potential association between decreased hip range of motion (especially decreased internal rotation) and ACL injury.
- Femoral and acetabular bone deformities may increase risk of ACL injury.
  - Decreased femoral head–neck offset
  - Increased alpha angle
  - Decreased center-edge angle
  - Femoral acetabular impingement
- Athletes with greater hip abduction strength may be less likely to sustain lower extremity injury.
  - Young female athletes should perform hip abduction strengthening exercises beginning around age 13.

12.3 Femoral Acetabular Impingement (FAI) and ACL Injury

As previously discussed, altered hip kinematics secondary to pathologic conditions such as FAI may increase a patient's susceptibility to ACL injury. FAI is a well-known hip condition caused by alterations in the bony anatomy of the hip. First described in 2003, Ganz and colleagues [29] coined the term *femoroacetabular impingement* to describe a "mechanism for the development of early osteoarthritis for most nondysplastic hips." FAI is due to abnormal contact between the proximal femur and acetabular rim that occurs during terminal motion of the hip, leading to lesions of the acetabular labrum and/or adjacent acetabular cartilage. Subtle, previously overlooked deformities of the proximal femur and acetabulum were recognized as the cause of FAI, including the presence of a bony prominence typically in the anterolateral head and neck junction (cam morphology), or changes caused by an abnormal acetabular rim abutting against a normal femoral head and neck (pincer deformity). Therefore, cam-type and pincer-type FAI deformities were introduced as two distinct mechanisms of FAI.

12.3.1 Cam FAI

Cam-type impingement is caused by an abnormal shear force between an aspherical femoral head and a normal acetabulum during hip flexion and internal rotation [30]. During motion, the cam deformity is rotated into the acetabular socket with a shearing-type injury pattern, causing a labral tear and delamination of the articular cartilage (Fig. 12.1). The damage is localized to the corresponding location where the abnormal head–neck junction and acetabular rim make contact. Eventually, there is separation of the labrum from the underlying subchondral bone (Fig. 12.2) that occurs at the transitional zone between the labrum and hyaline cartilage [31]. Johnston et al. [32] reported an association between the lack of femoral head–neck sphericity and the size of the cam lesion with the extent of acetabular chondral damage and delamination. These investigators noted more intra-articular damage in patients with a higher alpha angle (Fig. 12.3), including detachment of the labrum and full-thickness delamination of the articular cartilage. Bhatia et al. [33] and Ho et al. [34] have also noted this same finding.

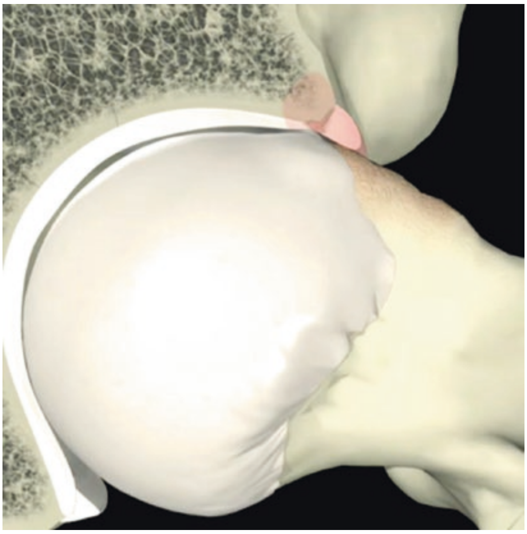

Fig. 12.1 During motion, the cam deformity is rotated into the acetabular socket with a shearing-type injury pattern, causing a labral tear and delamination of the articular cartilage

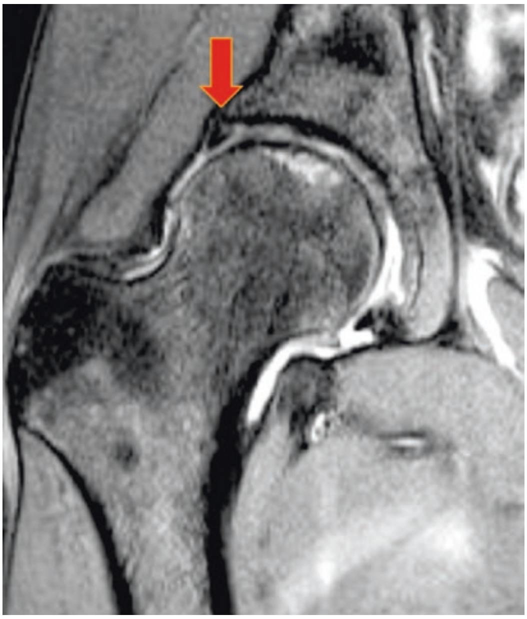

Fig. 12.2 MRI depiction of separation of the labrum from the underlying subchondral bone on the acetabular rim, occurring at the transitional zone between the labrum and hyaline cartilage

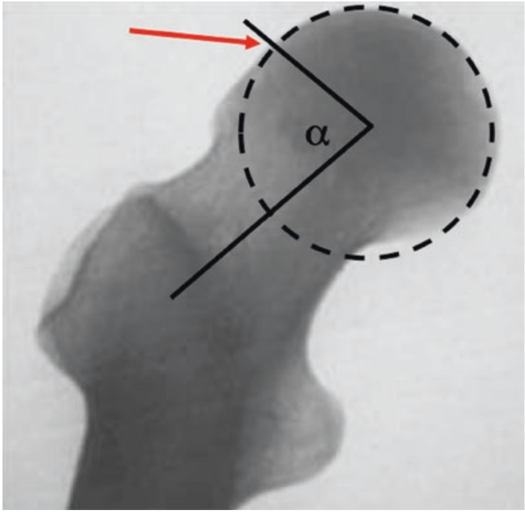

Fig. 12.3 Alpha angle measurement. There is an association between the lack of femoral head–neck sphericity and the size of the cam lesion with the extent of acetabular chondral damage and delamination. Higher alpha angles have been linked to more intra-articular damage, including detachment of the labrum and full-thickness delamination of the articular cartilage [20, 55, 61]

Advances in understanding the prevalence of cam morphology and the association with OA have improved our understanding of the pathophysiology of FAI. Several studies [35, 36] have established that cam morphology of the proximal femur (defined by a variety of metrics) is common among asymptomatic individuals. For example, Register et al. [36] revealed a prevalence of FAI in asymptomatic patients of 15%, while 69% of asymptomatic volunteers demonstrated a labral tear on magnetic resonance imaging. Frank et al. [35] revealed a prevalence of asymptomatic cam lesions in 37–54% of athletes and 23% of the general population. In light of these findings, a description of the femoral anatomy as a "cam morphology" rather than a cam deformity is now favored [37]. Similarly, FAI is better used to refer to symptomatic individuals and is not equivalent to cam morphology.

Interestingly, cam morphology appears to be significantly more common among athletes and may be a precursor for osteoarthritis in the future [35, 38, 39]. Siebenrock et al. [38] demonstrated the correlation of high-level athletics during late stages of skeletal immaturity and development of a cam morphology. A recent systematic review of nine studies found that elite male athletes in late skeletal immaturity were 2–8 times more likely to develop a cam morphology before skeletal maturity [40]. Finally, in a prospective study, Agricola et al. [41] found the risk of OA was increased 2.4 times in the setting of moderate cam morphology (α angle, >60°) over a 5-year period.

Therefore, given that FAI is quite common in the general population and especially in athletes, several authors have attempted to correlate FAI with downstream pathology along the lower kinetic chain. As discussed previously, Tainaka et al. [18] reported that hip rotation is inversely proportional to ACL injury risk. In other words, as hip rotation is reduced, the likelihood of experiencing an ACL rupture is increased. Further, in their single-leg pivot landing study, Beaulieu et al. [24] reported that peak ACL strain, which can predispose an athlete to an ACL tear, is increased by 1.3% with every 10° decrease in femoral rotation. Philippon et al. [15] reported that both males and females with a decreased femoral head–neck offset (alpha angle >60°) were at increased risk of having an ACL injury.

These findings suggest that that an athlete with cam-type FAI and a significant deficiency in hip internal rotation may experience significantly more peak ACL strain during landing than a healthy athlete, placing this structure at risk for injury [24]. Indeed, restricted internal rotation of the hip, as is the case in most patients with cam-type FAI [19], has been correlated with ACL ruptures and reruptures in soccer players [16, 21] and in professional American football athletes [22]. Patients with abnormally elevated alpha angles may also have diminished capacity at the hip to accommodate overall lower extremity internal rotation moments, potentially predisposing the knee (and other intra-articular structures) to a greater rotational stress. In this regard, Girard et al. [25] suggested that improving the femoral head–neck offset could result in an improved range of motion in the hip, specifically in flexion allowing the knee forces to be normalized.

12.3.2 Pincer FAI

Pincer-type FAI results from acetabular-sided deformities in which the acetabular deformity leads to impaction-type impingement with contact between the acetabular rim and the femoral head–neck junction. Pincer FAI causes primarily labral damage with progressive degeneration and, in some cases, ossification of the acetabular labrum that further worsens the acetabular overcoverage and premature rim impaction. Chondral damage in pincer-type FAI is generally less significant and limited to the peripheral acetabular rim or a contrecoup lesion in the posteroinferior acetabulum (Fig. 12.4).

Pincer-type FAI may be caused by acetabular retroversion, coxa profunda, or protrusio acetabuli. The definition of a pincer morphology has evolved significantly over the past several years. Through efforts to better define structural features of the acetabular rim that represent abnormalities, hip specialists now have a greater understanding of how these features may influence OA develop-

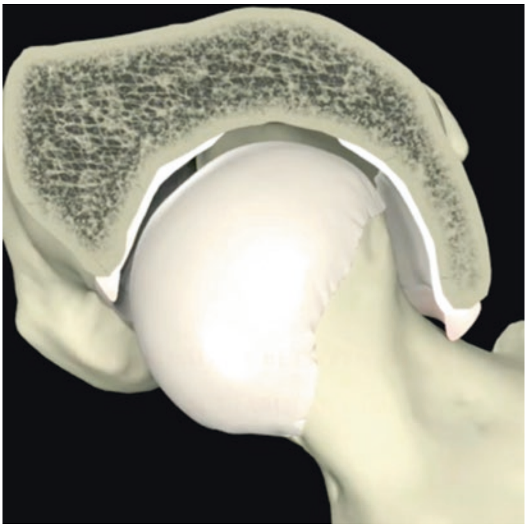

Fig. 12.4 Pincer-type FAI results from acetabular-sided deformities in which acetabular deformity leads to impaction-type impingement with contact between the acetabular rim and the femoral head–neck junction. Pincer FAI causes primarily labral damage with progressive degeneration and, in some cases, ossification of the acetabular labrum that further worsens the acetabular overcoverage and premature rim impaction. Chondral damage in pincer-type FAI is generally less significant and limited to the peripheral acetabular rim or a contrecoup lesion in the posteroinferior acetabulum

ment. One example of improved understanding involves coxa profunda, classically defined as the medial acetabular fossa touching or projecting medial to the ilioischial line on an anteroposterior (AP) pelvis radiograph. Several studies have found that this classic definition poorly describes the "overcovered" hip, as it is present in 70% of females and commonly present (41%) in the setting of acetabular dysplasia [42].

Acetabular retroversion is another type of pincer deformity that has been previously associated with hip OA. Although central acetabular retroversion is relatively uncommon, cranial acetabular retroversion is more common. Presence of a crossover sign on AP pelvis radiographs generally has been viewed as indicative of acetabular retroversion. However, alterations in pelvic tilt on supine or standing AP pelvis radiographs can result in apparent retroversion in the setting of normal acetabular anatomy and potentially influence the development of impingement [43, 44]. Zaltz et al. [45] reported that abnormal morphology of the anterior inferior iliac spine can also lead to the presence of a crossover sign in an otherwise anteverted acetabulum. Nepple et al. [46] recently found that a crossover sign is present in 11% of asymptomatic hips (19% of males) and may be considered a normal variant. A crossover sign can also be present in the setting of posterior acetabular deficiency with normal anterior acetabular coverage. Ultimately, acetabular retroversion might indicate pincer-type FAI or dysplasia, or simply be a normal variant that does not require treatment. Global acetabular overcoverage, including coxa protrusio, may be associated with OA in population-based studies, but is not uniformly demonstrated in all studies [39]. A lateral center edge angle of >40° and a Tönnis angle (acetabular inclination) of <0° are commonly viewed as markers of global overcoverage.

Beck et al. [31] examined 302 cases of FAI and found that 5% had an isolated pincer lesion, 9% had an isolated cam lesion, and 86% had a combination of these two abnormalities. Philippon and Schenker [47] found mixed FAI patterns to be the predominant cause of hip pain among athletes with complaints of decreased hip range of motion as well as impaired athletic performance. Athletes participating in ice hockey, soccer, football, and ballet were most affected.

Therefore, a majority of athletes present with a mixed picture of FAI, including both cam morphology and pincer defect. These factors may act in a synergistic fashion to further limit the hip range of motion and place the knee, and specifically the ACL, at increased risk of injury.

Critical Points

- Cam-type impingement caused by abnormal shear force between an aspherical femoral head and a normal acetabulum during hip flexion and internal rotation.
- Causes separation of labrum from underlying subchondral bone.
- Cam morphology more common among athletes may be a precursor for osteoarthritis.

- Athletes with cam-type FAI and significant deficiency in hip internal rotation may be at greater risk for ACL injury.
- Pincer-type FAI caused by acetabular-sided deformities causes labral damage with progressive degeneration. Chondral damage limited to peripheral acetabular rim.
- Pincer-type FAI caused by acetabular retroversion, coxa profunda, or protrusio acetabuli.
- Majority of athletes have both cam morphology and pincer defect.

12.4 Hip and Core Strength Deficits in Post-ACL Reconstruction State

The majority of secondary ACL injuries are caused by noncontact mechanisms [48], highlighting the alteration of neuromuscular control following primary ACL reconstruction. The risk of secondary ACL injury is approximately seven times the risk of primary ACL injury [49]. One of the major but often overlooked contributors to ACL reinjury is hip and core strength deficiency. An increasing body of literature has suggested that strength within the core and hip muscle groups may be influenced negatively by both an ACL injury and subsequent reconstruction procedure; specifically, weakness of hip flexors and extensors after ACL surgery has been noted. Hiemstra et al. [50] reported hip adductor weakness after hamstring autograft ACL reconstruction, which persisted up to 2 years after surgery in ACL-reconstructed knees compared with uninjured knees. Furthermore, Khayambashi et al. [6] studied isometric hip abduction and external rotation strength in 501 patients for one season and reported that 15 (3%) suffered an ACL tear. Importantly, the authors noted significantly lower hip strength in the ACL-injured patients.

Other lower extremity muscle groups have also been studied in the context of ACL reinjury. Hamstring strength alone has not been shown to have a significant effect on knee function following ACL reconstruction [51, 52]; however, hamstring activation may be important for the neuromuscular control of an ACL-reconstructed knee [51]. Moreover, deficits in hamstring strength may alter the hamstrings–quadriceps torque production ratio, which has been hypothesized to be one potential risk factor for primary ACL injury [1, 53–55].

Rehabilitation following ACL reconstruction is crucial to ensure good outcomes for the patient and to give athletes the best opportunity to return to high-level sport. The importance of rehabilitation comes into focus when considering that muscular deficits are observed following ACL reconstruction up to 2 years after surgery [56]. Much of the observed muscle weakness is centered in the hip and core muscle groups. The core musculature plays an important role in stabilizing the lower extremity, especially during knee movement [57]. The primary core muscles firing during reaction activities like running are the transversus abdominis and internal oblique. Trunk neuromuscular control has been implicated as a risk factor for knee ligament injuries [58, 59]; however, the current evidence for increases in trunk displacement and deficits in proprioception as risk factors for noncontact ACL injuries in female athletes is insufficient.

Because of the relationship between hip strength deficits and ACL injury, a growing body of literature of focused hip rehabilitation after ACL reconstruction has emerged. Stearns et al. [60] evaluated a hip-focused training program on the lower extremity during a drop–jump test and found that training resulted in significantly greater hip extensor strength and knee flexion. These findings lead these authors to conclude that focused hip rehabilitation creates favorable lower extremity kinematics to reduce ACL injuries. Paterno et al. [56] studied postural control and stability in 56 athletes after primary ACL reconstruction. The 13 athletes that suffered a second ACL injury had deficits in transverse plane hip kinematics and frontal plate knee kinematics during landing. These deficits were 92% sensitive for a second ACL injury. Dynamic single-limb tests have also been used to identify post-ACL reconstruction strength deficits. Performance in the single-limb hop test for distance in ACL-deficient patients has been reported to predict self-measured function 1 year after ACL reconstruction, with 71% sensitivity and specificity [61]. These findings indicate that decreasing or eliminating asymmetrical lower extremity movement after ACL reconstruction has the capacity to reduce secondary ACL injury risk and maximize performance.

Identifying and treating hip and core weakness in ACL-reconstructed athletes is crucial in getting the athlete back to competition. In a recent systematic review of return to sport rates following ACL injury, only 44% of athletes returned to sport after an average of 41.5 months after ACL reconstruction [62]. This level of return to sport may be secondary to the deficits in hip and core strength, leading to abnormal lower extremity kinematics during sport. This concept is supported by a recent study that demonstrated that aberrant lower extremity motion is a predictor of secondary ACL injury [56]. Rehabilitation of the ACL-injured patient must be performed in a bilateral fashion, because leg asymmetry has been demonstrated to greatly increase the risk of second ACL injury. Furthermore, attention should be directed toward strengthening the core to create optimal motion symmetry and equal external knee abduction control [63].

Critical Points

- One of the major contributors to ACL reinjury is hip and core strength deficiency.
- Weakness of hip flexors and extensors after ACL reconstruction has been documented.
  - Attention on hip strengthening after ACL reconstruction is critical.
  - Identifying and treating hip and core weakness is crucial for return to competition.
  - Rehabilitation must be done in a bilateral fashion.

12.5 FAI Treatment with ACL Injury

In patients with concomitant knee and hip pathology, it is pertinent for the physician to address both issues. In athletes, an ACL injury should take precedence due to its acuity and the increased stress imparted on secondary stabilizers of the knee, and should be reconstructed in a timely fashion. However, if the ACL-injured patient presents with concomitant, symptomatic FAI that is left untreated, this may increase the risk for reinjury of the reconstructed knee and potentiate chondral and labral pathology within the hip joint [15].

Improvements in hip arthroscopy techniques and instrumentation have led to hip arthroscopy becoming the primary surgical technique for the treatment of most cases of FAI after failure of nonoperative treatments. Hip arthroscopy allows for precise visualization and treatment of labral and chondral disease in the central compartment by traction, as well as complete decompression of bony impingement lesions on the femur and acetabulum in the peripheral compartment. The importance of preserving the acetabular labrum is now well accepted from clinical and biomechanical evidence [64–66]. As in previous studies in surgical hip dislocation, arthroscopic labral repair (vs. debridement) results in improved clinical outcomes [67, 68]. Labral repair techniques currently focus on stable fixation of the labrum while maintaining the normal position of the labrum relative to the femoral head and avoiding labral eversion, which may compromise the hip suction seal (Fig. 12.5).

Open and arthroscopic techniques have shown similar ability to correct the typical mild to moderate cam morphology in FAI [69]. Yet, inadequate femoral bony correction of FAI is the most common cause for revision hip preservation surgery [70]. Inadequate bony resection may be the result of surgical inexperience, poor visualization, or lack of understanding of the underlying bony deformity. Modern osteoplasty techniques focus on gradual bony contour correction that restores the normal concavity–convexity transition of the head–neck junction (Fig. 12.6). Overresection of the cam deformity may not only increase the risk of femoral neck fracture, but also may result in early disruption of the hip fluid seal from loss of contact between the femoral head and the acetabular labrum earlier in the arc of motion. In addition, a high range of motion impingement can be seen in various athletic populations (dance, gymnastics, martial arts, hockey goalies), and the regions of impingement may to be farther away from the classically described impingement [37]. Impingement in these situations occurs at the distal femoral neck and subspine regions, adding a level of complexity and unpredictability from a surgical standpoint. Nevertheless, in a patient with concomitant FAI and knee pathology, accurate and complete resection of the cam deformity is necessary to improve the patient's hip biomechanics and range of motion, and therefore decrease the risk for ACL injury or reinjury in the future.

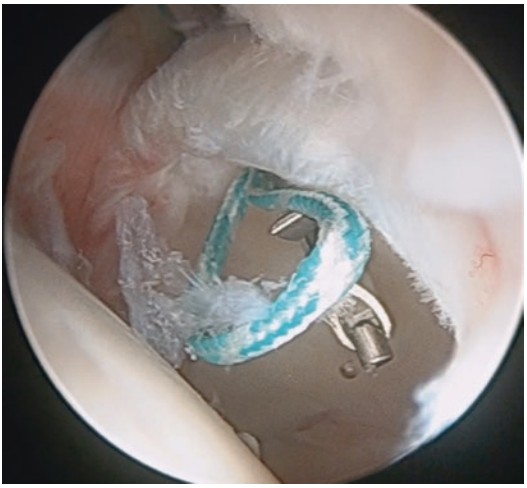

Fig. 12.5 The importance of preserving the acetabular labrum is now well accepted from clinical and biomechanical evidence [2, 36, 47]. As in previous studies in surgical hip dislocation, arthroscopic labral repair (vs. debridement) results in improved clinical outcomes [38, 44]. Labral repair techniques currently focus on stable fixation of the labrum while maintaining the normal position of the labrum relative to the femoral head and avoiding labral eversion, which may compromise the hip suction seal

Similar to the treatment of cam deformities, mild to moderate pincer-type deformities are also commonly treated with hip arthroscopy. As the understanding of pincer-type FAI continues to improve, many surgeons are performing less-aggressive bone resection along the anterior acetabulum. Severe acetabular deformities with global overcoverage or acetabular protrusion are particularly challenging by arthroscopy, even for the most experienced surgeons. Although some improvement in deformity is feasible with arthroscopy, even cases reported in the literature have demonstrated incomplete deformity correction and persistent functional disability. Open surgical hip dislocation may continue to be the ideal treatment technique for severe pincer impingement to improve hip and lower extremity biomechanics.

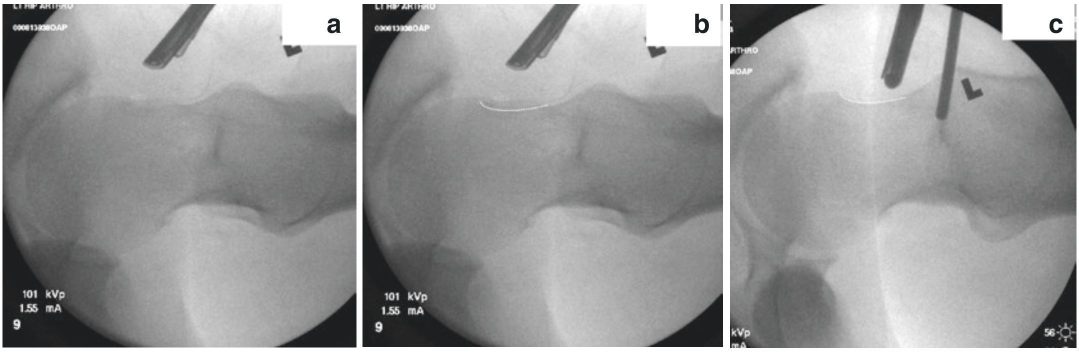

Fig. 12.6 Modern osteoplasty techniques focus on gradual bony contour correction that restores the normal concavity–convexity transition of the head–neck junction. (**a**), a proximal femoral intraoperative frog-leg fluoroscopy view before correction; (**b**), with a marked region of correction; and (**c**), after osteoplasty is complete. Overresection of the cam deformity may not only increase the risk of femoral neck fracture but also may result in early disruption of the hip fluid seal from loss of contact between the femoral head and the acetabular labrum earlier in the arc of motion

Table 12.1 Reduction in noncontact ACL injury incidence with Sportsmetrics program

Sportsmetrics neuromuscular training program: Reduction in ACL injury risk						
Trained athletes		Control athletes		Statistics		
Athletes (*n*)	Noncontact ACL injury rate[a]	Athletes (*n*)	Noncontact ACL injury incidence rate[a]	*P* value	Relative risk reduction (95% CI)	Number needed to treat[b] (95% CI)
700	0.03	1120	0.21	0.03	88 (6–98)	98 (59–302)

[a] Calculated per 1000 exposures

[b] Positive value to benefit, negative value to harm

Reprinted from Noyes FR, Barber-Westin SD: Noyes FR, Barber-Westin SD (2014) Neuromuscular retraining intervention programs: do they reduce noncontact anterior cruciate ligament injury rates in adolescent female athletes? Arthroscopy 30:245–255

Critical Points

- ACL-injured patient with concomitant symptomatic untreated FAI may be at risk for reinjury in the reconstructed knee and chondral and labral pathology in the hip joint.
- Hip arthroscopy primary techniques for FAI.
  - Arthroscopic labral repair improves clinical outcomes.
  - Modern osteoplasty techniques focus on gradual bony contour correction that restores the normal concavity–convexity transition of the head–neck junction.
- Mild to moderate pincer-type deformities commonly treated with hip arthroscopy.

12.6 The Role of the Hip in ACL Injury Prevention Efforts

ACL injury prevention efforts have made an incredible leap forward in recent decades. The first program of this type was Sportsmetrics, a neuromuscular knee ligament injury prevention program developed by Frank Noyes, M.D., and associates [4, 71]. There have since been a variety of ACL injury prevention programs all aimed at decreasing knee ligament injury risk by improving neuromuscular control in the lower extremity and thereby improving dynamic stability. Many investigations regarding the efficacy of this approach have since been conducted and guidelines now exist on their recommended utilization [72].

As demonstrated in the literature, abnormal hip muscle strength is a significant predictor of abnormal knee kinematics and therefore a risk factor for noncontact ACL injury [6]. Athletes with poor motor control of the lower extremities have increased valgus loading and malalignment during jump landing and other athletic endeavors. Because of this link, Sportsmetrics (along with other validated prevention programs) aims to improve neuromuscular control of hip, quadriceps, hamstring, and general lower limb musculature. Studies have demonstrated that athletes undergoing such interventions have improved overall lower limb alignment on the drop–jump test [73], improved hamstring strength, increased knee flexion angles on landing, and reduced deleterious knee abduction and adduction moments and ground reactive forces [71]. From a clinical outcomes standpoint, such interventions have demonstrated efficacy in reducing the risk of noncontact ACL injuries in female athletes participating in soccer and basketball (Table 12.1) [4]. Additionally, Sportsmetrics has been shown to enhance performance in female soccer [74], basketball [75], tennis [76], and volleyball players [73].

Conclusions

Current literature has demonstrated a relationship between hip range of motion and risk of ACL injury and ACL reinjury. An increasing body of literature supports the notion that females are at an increased risk of these injuries in part due to female pelvis anatomy, but also due to muscle weakness throughout the hip. All sports medicine professionals must be aware of the interplay between hip motion and ACL injury. Knowledge of this relationship is crucial so that athletes perform a comprehensive proper return to sport protocol including hip and core strengthening following ACL reconstruction.

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13

Gender Differences in Core Strength and Lower Extremity Function During Static and Dynamic Single-Leg Squat Tests

Mary Lloyd Ireland, Lori A. Bolgla,
and Brian Noehren

Abstract

This chapter discusses the principles of core strength and stability with regard to noncontact ACL injury. The single-leg squat test is described as a useful clinical tool to determine core stability. Associations between core strength, neuromuscular activity, and lower extremity function during this test are detailed. In addition, a newer dynamic single-leg squat test is described. These assessment tools are recommended to determine impairments, prescribe individualized interventions, and assess those athletes who may benefit from an ACL injury prevention training program.

13.1 Introduction

Annually, over 200,000 anterior cruciate ligament (ACL) tears occur in the USA [1, 2]. The cost to treat these injuries each year is conservatively estimated to be $1–2 billion [3, 4]. The long-term sequelae from the initial injury may increase the economic cost well above these estimates [5]. Based on these data, scientists have sought to develop ACL injury prevention programs to mitigate the risk of injury and costs [6–8].

Up to 70% of all ACL injuries involve a noncontact mechanism [9]. Female athletes have a 2.44 greater relative risk of injury risk of sustaining an ACL tear [10]. This injury is most likely to occur when performing an open cutting maneuver that involves deceleration and sudden changes in direction on a fixed foot. During this maneuver, female athletes tend to exhibit a greater amount of knee valgus, femoral internal rotation, and tibial external rotation, collectively referred to as *dynamic knee valgus* [11, 12]. Using a cadaveric model, Fung and Zhang [13] demonstrated how dynamic knee valgus can impart excessive strain of the ACL over the lateral femoral condyle. The greater amount of knee valgus is thought to be a result of poor neuromuscular

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control of the hip and trunk that affects females more so than males [14–16].

ACL injury etiology in the female athlete is a multifactorial problem that may result from anatomical/structural, hormonal, neuromuscular, and biomechanical factors [17]. Anatomical/structural and hormonal factors may contribute to injury in women but generally are not modifiable. However, neuromuscular and biomechanical factors are amenable to change and are thus a focus of much research. Specifically, women demonstrate lower extremity movement and muscle firing patterns that make them more susceptible to ACL injury. To explain these patterns and possible contribution to ACL injury, Ireland [15] described the "position of no return" shown in Fig. 13.1. The safe position (shown on the left) incorporates a more flexed hip and knee position which facilitates muscles of hip external rotation and abduction, lumbar spine extension, and hamstring activation to land in a safe, flexed hip, and flexed knee position. In the "position of no return" (shown on the right), the body is more upright, the back is flexed forward, the hip is in abduction/internal rotation, and the knee is less flexed which reduces the mechanical advantage of the muscles that are activated in the preferred position of safety. In support of the need for a stable and strong trunk and hip, Leetun et al. [16] reported that women who developed a lower extremity injury had weaker hip abduction and external rotation strength. More recently, hip external rotation weakness has been associated with ACL injury risk [18]. In addition to the hip, trunk strength and poor trunk control have also been implicated as risk factors for lower extremity injury [19–21].

For over 20 years, researchers have examined the interaction between hip and knee mechanics in the female athlete and reported faulty hip mechanics compared with males during landing and cutting maneuvers [22–26]. These studies typically employed the use of 3-dimensional

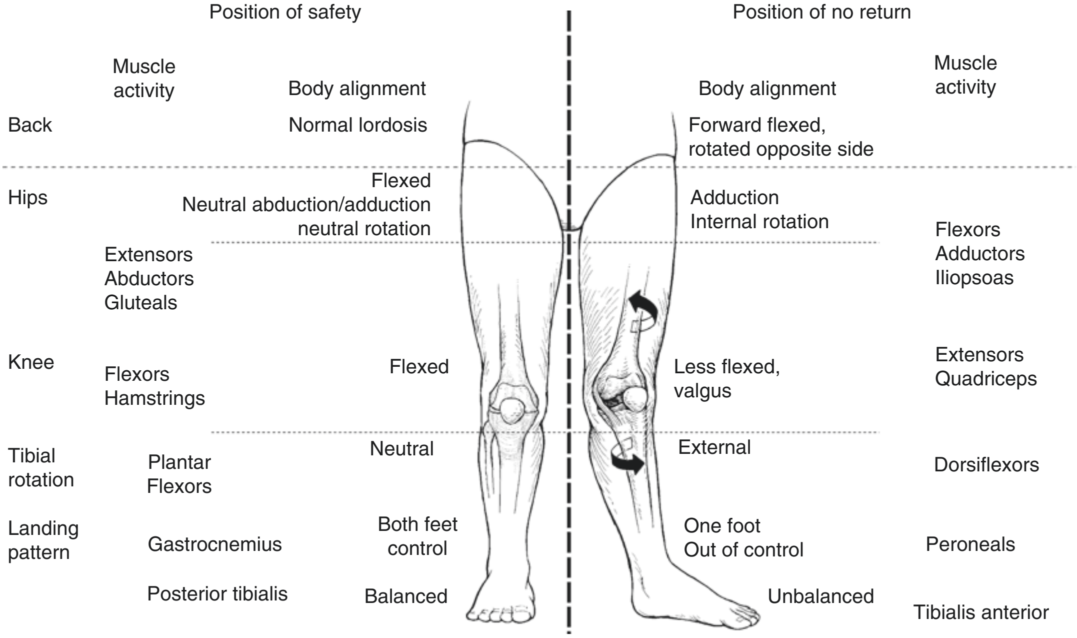

Fig. 13.1 Muscle activity and body alignment is shown for the position of safety *(left)* and "position of no return" (*right*). The position of safety occurs with knee flexed, hip flexed and neutral, and two-footed balanced landing. In contrast, the "position of no return" occurs when the body is more upright with the hips and knees less flexed, resulting in uncontrolled body rotation when landing. The muscle imbalance and position of trunk and joints places the knee at risk for ACL tear

(3-D) motion analysis systems which, although very precise, are not conducive for a clinical setting. To address this limitation, researchers have compared 3-D lower extremity hip and knee frontal plane alignment with that collected using 2-dimensional (2-D) techniques that can be replicated in the clinic. Data from these investigations have found that examination of frontal plane movement may be a useful screening tool to identify athletes who may exhibit increased dynamic knee valgus during athletic maneuvers [27, 28].

The single-leg squat test is a common screening tool that clinicians may use to assess frontal plane lower extremity motion. An advantage of this screening tool is that it allows the examiner to assess control and position of the trunk and entire lower extremity. For example, in normal healthy individuals, differences have been seen between males and females as they perform this test. An example is shown in Fig. 13.2a, where the male exhibits proximal control as evidenced by a straight hip-over-knee-over ankle position. In contrast, the female (Fig. 13.2b) has a valgus knee position driven proximally by hip internal rotation and adduction on a fixed pronated foot with tibial external rotation. A side view shown in Fig. 13.3a shows the male demonstrating the preferred lumbar spine position, with a posteriorly rotated pelvis. However, the female (Fig. 13.3b) has a forward lumbar spine position, and the pelvis is anteriorly rotated. She exhibits less hip flexion than the male. This pelvis position drives the hip into internal rotation and adduction, potentially creating a risk position for ACL injury.

The purpose of this chapter is to examine the use of the single-leg squat as a screening tool to identify the female athlete who may be at increased risk for sustaining an ACL injury. This chapter will begin with a brief overview of the core and core stability and explain the use of the single-leg squat as a measure of core stability. The remaining sections will provide information on the association between core strength, neuromuscular activity, and lower extremity function during a single-leg squat and identify gender differences for these variables. It is our intent that the reader can use this information to identify the at-risk female who may benefit from participation in an ACL injury prevention program.

Fig. 13.2 Single-leg mini-squat, done while standing on a step. (**a**) The male athlete has good balance, with hip-over-knee-over-ankle control and a level pelvis. (**b**) The female athlete has valgus at the knee, resulting from the proximal body position of femoral internal rotation and adduction, leading to subsequent tibia external rotation and pronation, in order to remain upright doing this maneuver. There is also a pelvic drop on the side of the squat

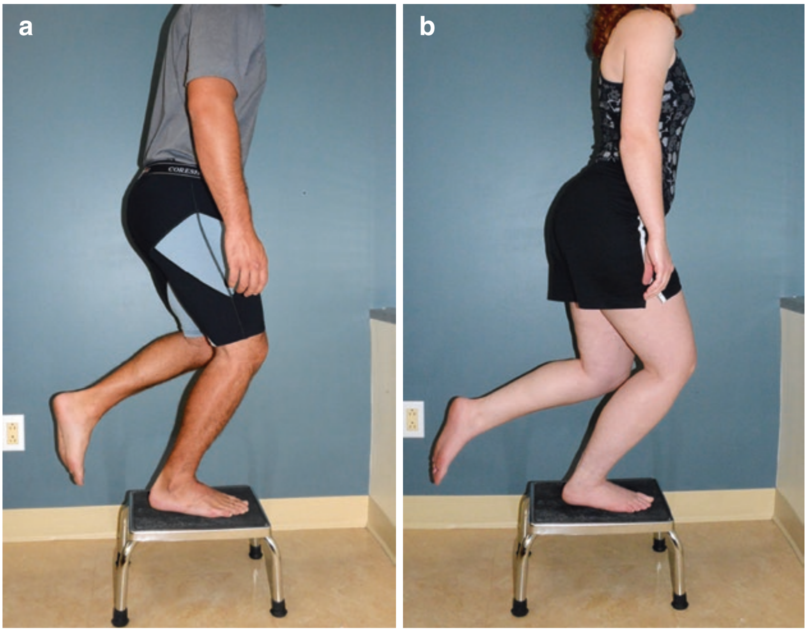

Fig. 13.3 Single-leg mini-squat shown from the side. (**a**) The male demonstrates a more posteriorly rotated pelvis, with the lumbar spine in neutral, and better balance with the knee flexed. (**b**) The female has a forward thoracic lumbar spine movement with pelvic drop and anterior pelvis rotation

Critical Points

- As data have suggested an increased prevalence of osteoarthritis following ACL injury, attention has been directed toward identifying athletes who may be at risk for injury and may benefit from participation in an ACL injury prevention program.
- ACL injury etiology is a multifactorial knee problem that is likely influenced by core function.
- The single-leg squat is a clinically useful tool for identifying faulty movements of the core and lower extremity that may make an athlete susceptible to ACL injury.

13.2 Definition and Principles of Core Stability

The core is defined as the lumbopelvic-hip complex which includes the trunk, thoracic-lumbar spine, pelvis, hip joints, and all ligamentous and muscular components associated with them. Stability is the ability of a system to resist change. Pope and Panjabi [29] defined a stable object as one in an “optimal” state of equilibrium. Core stability is achieved when the lumbopelvic-hip complex resists change to create an optimal state of equilibrium.

To obtain an optimal state of core equilibrium, a complex coordination of many passive and active elements must occur. Bony architecture and soft tissue compliance contribute to passive stability, and muscle contraction provides the active component of stability [30]. The active component provides stability through increased abdominal pressure, spinal compressive forces, and trunk and hip muscle stiffness [30]. If one or more of these restraints is damaged or weakened, the core may be in suboptimal equilibrium. Therefore, the maintenance of lumbopelvic-hip complex stability requires a highly coordinated interaction of the spine and hip musculature to provide trunk and hip stiffness.

Stability of the spine is one key component of core equilibrium. Due to the spine’s inherent unstable nature, coordination of muscular and neural elements is necessary [31]. Cholewicki and VanVliet [32] examined spinal stability and reported that no muscle contributed >30% to overall stability.

Activation of trunk musculature provides a stable platform for lower extremity movement. Hodges and Richardson [33] examined trunk musculature onset during lower extremity movement. Their findings highlighted the importance of the transverse abdominis and the multifidus contraction, in advance of lower extremity movement. They concluded that co-contraction of these antagonist muscle groups increased intra-abdominal pressure to facilitate spinal stiffness [30]. Maintenance of core stability occurs when spine stability and trunk musculature activation is in synchrony.

Hip stability also contributes to core stability, as well as dynamic lower extremity alignment. The gluteus medius, gluteus minimus, and upper fibers of the gluteus maximus provide stability in the frontal plane [34]. Together, these muscles work to maintain the pelvis in a level position during single-leg weight-bearing activities. Due to the triplanar orientation of its fibers, the gluteus maximus affords additional stabilization via its ability to control hip internal rotation [35]. The hip external rotators also may play a significant role in stability and injury prevention. Souza and Powers [36] found that hip extensor weakness was a predictor of increased hip internal rotation during running in females with anterior knee pain. Leetun et al. [16] assessed trunk and hip strength in basketball and track athletes prior to their competitive seasons. They then prospectively followed these athletes to determine those that subsequently sustained a lower extremity injury. Of all muscle performance measures taken, only strength of the short hip external rotators (e.g., piriformis, quadratus femoris, obturator internus, superior gemellus, and inferior gemellus) was deemed important for predicting athletes who ultimately incurred a lower extremity injury.

In summary, an emerging body of evidence has provided important information regarding the role of the core on lower extremity function. However, most investigations have been conducted in a laboratory setting not conducive for everyday clinical assessment. The single-leg squat is a clinical tool that can be helpful for assessing the influence of the core on lower extremity function during dynamic movement. The remaining sections provide additional information for the use of this assessment tool.

Critical Points

- Core stability can be defined as the ability of the lumbopelvic-hip complex to resist change and maintain an optimal state of equilibrium.
- A highly coordinated interaction of active and passive elements is necessary to provide a base for lower extremity movements.
- Co-contraction of abdominal and spinal musculature contributes to core stability by increasing intra-abdominal pressure and spinal stiffness.
- Hip musculature provides stability by maintaining a level pelvis and controlling femoral rotation.

13.3 Use of the Single-Leg Squat as a Measure of Core Stability

Since core stability involves the interaction of many complex elements, the development of clinical measures is difficult. The ideal test is one that is reliable, valid, and easily administered in a busy clinical setting. The single-leg squat is one such test that does not require any devices other than an examiner. The test is typically performed with the patient standing on the floor or on a foot stool in front of the examiner. The patient is instructed to stand on one lower extremity, squat to a desired level of knee flexion, and then return to the starting position. There are no instructions given for the position of the hands; they may either be placed on the hips or left hanging free. The examiner notes the patient's overall trunk control as well as the position of the hip, knee, and foot (see Sect. 13.4). Although various descriptions of the test exist, all focus on trunk and lower extremity control and position [37–40]. The most common variation between tests has been the squat depth.

The goal of the single-leg squat test is to identify the athlete who may have weakness or poor control of the core and hip musculature that make the knee prone to injury. Increased hip adduction and internal rotation during the single-leg squat suggest poor hip muscular control and greater reliance on quadriceps activity for knee control [40]. Increased quadriceps activity, especially with the knee in a minimally flexed position, may cause increased anterior tibial translation and strain on the ACL [41, 42].

The usefulness of any clinical tool depends on its reliability and validity. Munro et al. [43] examined the reliability of using the frontal plane projection angle (FPPA) as described by Willson et al. [39] to measure dynamic knee valgus during a single-leg squat. For this purpose, subjects were instructed to squat down as far as possible (to a minimum of 45° knee flexion). At the point of the greatest knee flexion angle, the investigators measured the FPPA. The FPPA was formed by drawing one line from the middle of the proximal femur to the middle of the tibiofemoral joint and a second line between the middle of the tibiofemoral joint and the ankle mortise (Fig. 13.4). These investigators reported between-day intraclass correlation coefficients of 0.88 and 0.72 for males and females, respectively, indicating good reliability.

Ageberg et al. [37] determined the reliability and validity of a similar single-leg squat test. Instead of measuring the FPPA, these researchers used a dichotomous rating system to quantify frontal plane knee motion. For this purpose, two experienced clinicians rated subjects as having either a "knee-over-foot" or a "knee-medial-to-foot" position when performing a single-leg squat to maximum knee flexion. All subjects performed five trials of the test at a standardized rate (20 squats/min). Subjects rated as having a "knee-over-foot" position performed at least three of the five trials with the knee aligned over or lateral to the second toe. Those who performed at least three of the five trials with the knee aligned medial to the second toe were classified as having a "knee-medial-to-foot" position. This method had excellent between-rater reliability as evidenced by a kappa value of 0.92 and a 96% agreement.

To establish validity of the single-leg squat test, Ageberg et al. [37] concurrently collected 3-D motion analysis data. Findings from the 2-D analysis showed that the subjects who received a

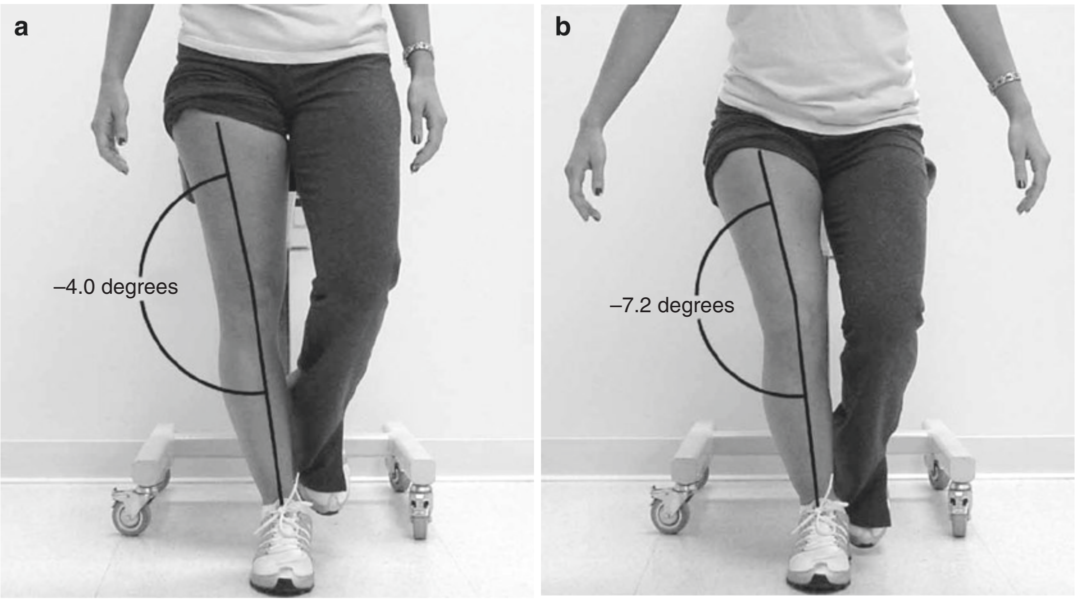

Fig. 13.4 The measurement of the frontal plane projection angles doing a single-leg stance (**a**) and single-leg squat (**b**). The angle is measured between two lines, the midpoint of the knee joint to midpoint of the ankle mortise and on the anterior superior iliac spine to the midpoint of knee joint. Reproducible measurements can be documented with a camera during positions of knee flexion and normalized based on height of the subject, with knee flexion controlled by the stool height behind the subject as shown. (Reprinted with permission from Willson et al. [39])

"knee-medial-to-foot" rating exhibited a greater peak thigh angle (in relation to the horizontal plane) that was more medially oriented relative to the knee. This orientation suggested that these subjects completed the single-leg squat with the knee in a more valgus position. Furthermore, data from the 3-D analysis revealed greater hip internal rotation in these same subjects. In summary, motion analysis data confirmed the ability of the observers to identify subjects who performed the test with a less-than-optimal hip position.

Due to its simplicity, reliability, and validity, the single-leg squat test is useful for evaluating female athletes who might be at risk for sustaining an ACL injury. The next section will highlight the association between core strength, neuromuscular activity, and lower extremity function. Understanding these interactions may assist the clinician with identifying impairments that could place an athlete at risk for sustaining a knee injury.

Critical Points

- The single-leg squat is an easy clinical test with established reliability and validity.
- It is recommended that the reader refer to the primary resources to ensure appropriate test administration and data interpretation.

13.4 Association Between Core Strength, Neuromuscular Activity, and Lower Extremity Function During a Single-Leg Squat

The main purpose of the single-leg squat assessment is to provide information regarding overall trunk and lower extremity strength, neuromuscular control, and quality of movement. When using this assessment tool, the clinician looks for the following:

- Erect trunk
- Minimal hip flexion
- Level pelvis (frontal plane)
- Abducted and externally rotated hip
- Knee over second toe position

Together, this posture suggests the athlete's ability to maintain good trunk, pelvis, and hip position during a dynamic movement.

13.4.1 Core Strength and Lower Extremity Function

Willson et al. [39] were one of the first investigators to examine the association between trunk, hip, and knee isometric strength and the knee FPPA during a single-leg squat. These investigators reported a significant correlation between increased trunk extensor ($r = 0.26$; $P = 0.05$), trunk lateral flexor ($r = 0.27$; $P = 0.04$), and hip external rotator ($r = 0.40$; $P = 0.004$) strength and a neutral FPPA (an angle closer to 0°). Although not significant, a trend existed for the importance of hip abductor strength ($r = 0.23$; $P = 0.07$). Regarding knee strength, the investigators reported a significant correlation between knee flexor ($r = 0.33$; $P = 0.02$), but not knee extensor ($r = 0.23$; $P = 0.12$), strength and the FPPA. Although the knee flexors (hamstrings) function primarily as a knee flexor, it was noteworthy that the hamstrings also assist with hip extension. This orientation may account for the significant association found between the knee flexors and FPPA.

Stickler et al. [44] conducted a similar study in women. This study found greater correlations between increased hip abductor ($r = 0.47$; $P = 0.002$), hip extensor ($r = 0.40$; $P = 0.012$), hip external rotator ($r = 0.46$; $P = 0.003$), and trunk lateral flexor ($r = 0.43$; $P = 0.006$) strength and a neutral FPPA. The multiple regression analysis showed that hip abductor strength accounted for 22% of the variation in FPPA. Clinically, this finding suggested that the FPPA would improve 0.2° for every 1% increase in isometric hip abductor strength (expressed as percent body mass). Such improvement may be functionally important for women with hip abductor weakness. Moreover, performance during a SLS may be more helpful for identifying strength deficits in females compared with males.

Using an isokinetic dynamometer to measure hip and knee strength, Claiborne et al. [45]

reported a significant negative correlation between concentric peak hip abductor ($r = -0.37$; $P < 0.05$), knee flexor ($r = -0.43$; $P < 0.001$), and knee extensor ($r = -0.37$; $P < 0.05$) torque and knee valgus during a single-leg squat. Furthermore, these three variables were significant predictors of the amount of knee valgus during a single-leg squat. It was noteworthy that these findings identified knee strength as a significant factor. Although the core and hip can help stabilize the knee, this investigation highlighted the importance of the knee muscles. Subsequent works have examined trunk and hip muscle function and single-leg squat performance and reported similar findings (Table 13.1).

Although researchers [39, 44, 45] reported significant associations between isometric strength measures and concentric peak torque and knee valgus during a single-leg squat, correlation coefficients were weak to moderate at best [46]. A possible reason might have been that these strength measures did not reflect muscle function during a dynamic task. As described above, the hip abductors and external rotators work synergistically in an eccentric manner to control hip adduction, hip internal rotation, and contralateral pelvic drop during weight-bearing activities [34].

To account for this type of muscle demand, Baldon Rde et al. [47] examined the relationship between eccentric hip abductor and external rotator peak torque and lower extremity kinematics during a single-leg squat in males and females. Regarding eccentric hip abduction, a significant association existed between hip abductor torque and hip adduction ($r = -0.55$; $P < 0.001$) and hip abductor torque and knee varus ($r = 0.49$; $P = 0.004$). No significant correlation existed between hip abductor torque and hip internal rotation. When analyzed by gender, greater associations existed for women. Results from this analysis revealed correlations between hip abductor torque and hip adduction ($r = -0.52$; $P = 0.03$), hip internal rotation ($r = -0.47$; $P = 0.04$), and knee varus ($r = 0.61$; $P = 0.01$) for women.

Table 13.1 Summary of findings from additional studies that have examined the influence of trunk and hip muscle strength on single-leg squat performance

Study	Muscle groups assessed	Single-leg squat performance rating	Relevant findings
Baldon Rde et al. [47]	• Hip abductors • Hip external rotators	3-dimensional motion analysis of pelvis, femur, and knee	• Moderate negative correlation between eccentric hip abductor torque and femur and knee adduction • Moderate negative correlation between eccentric hip external rotator torque and femur adduction • Moderate positive correlation between eccentric hip external rotator torque and contralateral pelvic elevation and knee adduction
Crossley et al. [56]	• Hip abductors • Hip external rotators • Trunk lateral flexors	Consensus panel of five experienced clinicians who used established criteria to rate single-leg squat performance as “good,” “fair,” or “poor”	Subjects who demonstrated “good” performance generated greater hip abductor and trunk lateral flexor torque
Willy and Davis [52]	• Hip abductors • Hip external rotators	3-dimensional motion analysis of the pelvis, femur, and knee	• Following training, subjects generated greater hip abductor and external rotator torque • Subjects in the training group also demonstrated less hip adduction, less hip internal rotation, and greater contralateral pelvic elevation during a single-leg squat • Controls exhibited no changes in strength or single-leg squat performance

For eccentric hip external rotation, the only significant correlations were between hip external rotator torque and hip adduction ($r = -0.47$; $P = 0.006$) and knee varus ($r = 0.36$; $P = 0.04$). No significant correlations existed when analyzing data for males and females separately. It was noteworthy that correlation coefficients were relatively higher between eccentric hip abductor torque and knee valgus than those reported by prior works [39, 45]. Therefore, additional investigations should continue to examine eccentric strength because it better emulates the demands placed on the hip during weight-bearing activities.

Recent works also have examined the effect of hip muscle fatigue on lower extremity kinematics during a single-leg landing. While some studies [24, 48] reported altered kinematics following a fatigue protocol, others [49, 50] have not shown this effect. To date, Weeks et al. [51] are the only investigators to investigate the impact that fatigue has on single-leg squat performance. Prior to the fatigue protocol, males demonstrated significantly less peak pelvic rotation toward the stance limb, peak hip internal rotation, hip adduction range of movement, hip rotation range of movement, and medial-lateral knee motion distance (a measure of knee valgus) during a single-leg squat compared with females. No between-gender differences occurred at the trunk. After the fatigue protocol, all subjects, regardless of gender, demonstrated significant increases in peak trunk flexion, peak trunk rotation toward the stance limb, peak pelvic obliquity and rotation away from the stance limb, and increased hip adduction range of movement. However, no changes occurred with respect to the medial-lateral knee motion distance. These findings provided preliminary data on the negative impact that fatigue may have on neuromuscular control of the core. Additional studies are needed to better understand the interrelationship between muscle fatigue and single-leg squat performance.

In summary, evidence to date supports the influence of trunk and hip muscle function on the dynamics of lower extremity movement during a single-leg squat. These findings suggest that the trunk extensors and lateral flexors, along with the hip abductors, may stiffen the core and stabilize the pelvis. The hip external rotators may optimize knee position by minimizing the degree of hip internal rotation. More importantly, Zazulak et al. [20] assessed trunk control in a group of collegiate athletes and prospectively followed them to determine which athletes incurred a knee injury. These investigators identified decreased trunk control as a significant risk factor for knee injury, especially for the female athlete. As discussed earlier, Leetun et al. [16] also prospectively followed athletes over a competitive season. Athletes with less hip external rotator and hip abductor strength were more likely to sustain a lower extremity injury. Finally, preliminary data have shown improvement in single-leg squat performance in females with evident hip weakness who participated in a 6-week training program comprised of hip-strengthening exercise and movement education [52]. Section 13.5 provides additional data with respect to gender differences in core strength and lower extremity function during a single-leg squat.

13.4.2 Core Neuromuscular Activity and Lower Extremity Function

Zeller and colleagues [40] were the first to compare electromyographic (EMG) activity (Table 13.2) and trunk and lower extremity kinematics (Table 13.3) between males and females during a single-leg squat. Overall, females generated greater muscle activation than males for all muscles. Furthermore, females exhibited lower extremity

Table 13.2 A comparison of mean (standard deviation) muscle amplitudes, expressed as a percent of a maximal voluntary isometric contraction, between males and females during a single-leg squat [40]

Muscle group	Males	Females
Trunk		
Rectus abdominis	22.9 (41.0)	8.5 (9.0)
Erector spinae	39.8 (7.6)	45.5 (29.8)
Hip		
Gluteus maximus	74.5 (58.7)	97.9 (38.2)
Gluteus medius	78.5 (81.8)	97.9 (38.2)
Knee		
Rectus femoris	34.3 (16.4)	78.8 (26.1)
Vastus lateralis	89.4 (48.1)	164.6 (100.1)
Biceps femoris	24.8 (18.9)	143.0 (351.5)

Table 13.3 A comparison of mean (standard deviation) maximum range of motion, expressed in degrees, for the trunk, hip, and knee between males and females during a single-leg squat [40]

Motion	Males	Females
Trunk		
Flexion	30.5 (13.7)	29.5 (10.1)
Lateral flexion	26.4 (20.1)	9.8 (9.1)
Hip		
Flexion	60.0 (8.1)	69.1 (8.4)
Extension	12.5 (5.6)	8.5 (5.7)
Adduction	14.6 (5.4)	17.8 (6.3)
Knee		
Flexion	89.5 (6.2)	95.4 (6.2)
Varus	14.4 (13.1)	6.4 (8.5)
Valgus	5.1 (4.9)	7.0 (7.0)

movement patterns indicative of less-than-optimal trunk, hip, and knee control. For example, males demonstrated similar trunk flexion but 2.7 times greater trunk lateral flexion, as females. Males also exhibited 1.5 times greater hip extension, whereas females had 1.2 times greater hip adduction. Together, these comparisons showed that males performed the single-leg squat task with the trunk, pelvis, and hip positioned in a more neutral manner. Furthermore, females completed the task with knee valgus 1.5 times greater than males.

Important patterns of trunk, hip, and knee muscle activity also existed. Males generated 2.7 times greater rectus abdominis activity but relatively similar erector spinae activity as females. These values suggested better abdominal activation that may have allowed males to maintain a more upright and symmetrical trunk position. Furthermore, females generated 1.3 times greater gluteus maximus and medius activity, 2 times greater quadriceps activity, and over 6 times greater biceps femoris activity. This pattern may have reflected the need for greater hip and knee muscle activation to compensate for less co-activation between the trunk flexors and extensors. Together, these findings suggested the following:

- Males maintained an upright and symmetrical trunk position and exhibited a better balance between erector spinae and rectus abdominis muscle activity.
- Females completed the task with more hip adduction and knee valgus and required greater muscle activity to complete the task. Increased muscle activity most likely reflected increased neural drive compared to males to maintain hip and knee position [53–55].
- When examined simultaneously, males demonstrated better co-activation between the trunk and hip muscles that resulted in a more optimal trunk, hip, and knee position during the single-leg squat.

In summary, findings from Zeller et al. [40] support the “position of no return” [15] for explaining the influence of faulty trunk and hip function on the knee. Subjects who maintained the trunk and hip in a more neutral position and generated more symmetrical trunk and hip muscle activity performed the single-leg squat with the knee in less valgus.

Crossley et al. [56] examined hip abductor performance during a single-leg squat (Table 13.1). This study reported that subjects who performed this task with good control generated greater hip abductor and lateral trunk flexor torque during isometric strength testing. These investigators also examined gluteus medius activation during a step-up maneuver. Results from this aspect of the study showed that subjects who demonstrated greater lower extremity control during the single-leg squat also had earlier activation (onset) of the gluteus medius during the step-up task. Crossley’s data suggested that subjects who performed poorly on a single-leg squat test not only exhibited diminished hip and trunk strength but also delayed gluteus medius onset during a stepping task. This delayed muscle activation may hinder pelvic and hip stability during dynamic activities.

Nguyen et al. [54] investigated the interactions between hip muscle activation and lower extremity joint excursion during a single-leg squat. Decreased peak gluteus maximus activity was reported to be a predictor of increased hip internal rotation excursion. Conversely, increased peak gluteus maximus activity was a predictor of knee valgus excursion. These investigators surmised that different hip activation strategies may exist for controlling hip motion compared to knee motion.

Hollman et al. [57] compared hip abductor and extensor strength as well as gluteus medius and gluteus maximus activity during a single-leg squat in females classified as performing a single-leg squat using "good" and "poor" form. No between-group differences existed for hip abductor and extensor strength. However, there was a significant association between decreased gluteus maximus activity and increased knee valgus angle. Therefore, neuromuscular retraining, rather than strengthening exercise, may be a more important focus to decrease knee valgus during functional tasks [58, 59].

Findings from both studies [54, 57] highlighted the stabilizing effect of the gluteus maximus on knee control. Powers [35] has advocated the importance of gluteus maximus function due to its ability to resist hip flexion, hip adduction, and hip internal rotation. These muscle actions may explain the importance of gluteus maximus, and not gluteus medius, activity on knee valgus during a single-leg squat.

13.4.3 Core Engagement and Lower Extremity Function

To our knowledge, Shirey et al. [38] were the first to examine the influence of volitional core engagement on lower extremity function during a single-leg squat in 14 females. Subjects were put into either a low or high core strength group based on scores determined using methods described by Sahrmann [60]. Next, these investigators collected frontal plane kinematic data during a single-leg squat under two conditions: no volitional core activation and volitional core activation (e.g., "engage the abdominal muscles" as instructed during initial core strength testing). Findings from this investigation showed reduced medial-lateral hip movement during volitional core activation for all subjects, regardless of the core strength score. Shirey et al. [38] concluded that subjects with low core scores may benefit from additional training. Together, these results implied that core training may improve lower extremity performance during a single-leg squat. Additional investigations are needed to determine if a similar effect will occur during more dynamic activities.

Critical Points

- Core strength influences the quality of lower extremity kinematics during a single-leg squat.
- Individuals with good quadriceps strength demonstrate less knee valgus during a single-leg squat.
- EMG data have suggested that similar activation levels between the trunk flexors and trunk extensors, as well as the gluteus maximus and gluteus medius, can positively affect trunk and lower extremity kinematics during a single-leg squat.
- Evaluation of muscle strength based on single-leg squat performance (i.e., the degree of knee valgus) may be more meaningful for females than males.
- Volitional activation of the core musculature may enhance lower extremity function during a single-leg squat.

13.5 Gender Differences During a Single-Leg Squat

To date, most studies [11, 12, 22, 61–65] have examined gender differences during running, cutting, and drop-landing tasks, with limited data available with respect to the single-leg squat test. Sections 13.4.1 and 13.4.2 provided an overview of the interrelationship between core strength, neuromuscular activity, and lower extremity function during a single-leg squat. While these sections briefly addressed gender differences, the purpose of this section is to compile the available evidence presented above in a manner to identify gender differences during a single-leg squat. It is our intent that the clinician may use this information to better identify core impairments that may make the female athlete more susceptible to ACL injury.

Zeller et al. [40] were the first to examine EMG activity (Table 13.2) and kinematics (Table 13.3) between males and females during a single-leg squat. Findings from this study showed that males demonstrated better co-contraction of the trunk and hip muscles that resulted in a more vertical trunk position in combination with less hip adduction and knee valgus. This pattern suggested that symmetrical muscle co-contraction between the trunk and hip muscles stabilizes the core to promote controlled lower extremity movement [32, 33]. Zazulak et al. [20] also reported poor trunk neuromuscular control as a predictor of lower extremity injury in the female athlete. A limitation of this study was the omission of core strength measures. Therefore, it remained elusive the extent that core strength might have had on lower extremity kinematics.

Willson et al. [39] compared isometric strength and the FPPA during a single-leg squat in 22 male and 22 female athletes. Clinically important associations existed for trunk lateral flexor, trunk extensor, hip abductor, hip external rotator, and knee flexor isometric strength and the FPPA when examining data combined for all subjects. When comparing strength and FPPA measures between genders, males exhibited greater isometric strength for all trunk and hip muscles except the trunk extensors. Males also tended to move toward a more neutral knee position during the single-leg squat. Conversely, females had less trunk and hip isometric strength and higher FPPA values. Unlike males, they moved toward a more valgus knee position.

In a subsequent investigation, Baldon Rde et al. [47] found similar gender differences with respect to knee movement during a single-leg squat. As in the Willson et al. study [39], women generated significantly less eccentric hip abductor and external rotator torque than men during strength testing. Females also exhibited greater contralateral pelvic drop excursion (4.80 ± 2.37° vs. 2.43 ± 2.07°) and greater hip adduction excursion (4.16 ± 2.97° vs. 0.01 ± 2.63°) than males. These excursions were accompanied with females moving into a greater amount of knee valgus than males (4.73 ± 4.84° and 0.33 ± 3.48°, respectively).

As discussed in Sect. 13.4.1, Baldon Rde et al. [47] determined correlations between eccentric hip abductor strength and lower limb kinematics using data compiled for all subjects and then based on gender. Correlation coefficients using only data for female subjects showed significant negative correlations between peak abductor torque and hip adduction and hip internal rotation and a significant positive correlation between hip abductor torque and knee varus. However, no significant correlations existed when analyzing these same variables for males. This finding suggested that females may rely more on hip muscle function to control frontal plane knee movement. Therefore, the single-leg squat test may be more applicable for the assessment of female athletes.

Critical Points

- Females exhibit trunk and hip weakness that can lead to greater hip adduction, hip internal rotation, contralateral pelvic drop, and knee valgus than males during a single-leg squat.
- Females generate greater hip and knee muscle EMG activity during a single-leg squat that suggests a greater reliance on the hip and knee muscles for lower extremity control.
- Stronger correlations exist between hip abductor strength and lower extremity kinematics for females than males.

13.6 Development of a New Dynamic Single-Leg Squat Test

To date, most assessments of the single-leg step-down test performance have focused on static function. However, performance of numerous repetitions may provide additional detail into muscle function and control not captured in a static test. Recently, investigators have focused on a timed single-leg step-down test as a potential answer to this challenge. For example, Kline et al. [66] found that the number of single-leg step downs performed at 3 months post-ACL reconstruction predicted a 6-month knee biomechanics during a self-selected run. The timed single-leg step-down test proved to be a better predictor than the Y Balance Test for knee flexion excursion and the knee extensor moment.

Additionally, the timed single-leg step-down test performed as well as isometric quadriceps strength testing for the knee extensor moment and was the only predictor of knee flexion excursion. These results suggested that the timed single-leg step-down test can provide clinicians early objective data on functional performance during dynamic activities such as running.

Recently, Burnham et al. [67] investigated the relationship of hip and trunk muscle function to timed single-leg step-down function. These investigators evaluated the effect of isometric hip abduction strength, hip external rotation strength, hip extension strength, as well as plank and side plank time, on the number of single-leg step downs performed in 60 s. All tests significantly correlated with timed single-leg step-down test performance. However, only plank time was significantly predictive of the number of single-leg step downs. This study also provided important normative data; on average, healthy males performed 40 and females performed 37 single-leg step downs in 1 min. This study has helped to provide important reference values as well as insights into the relative contribution of the hip and trunk to successful performance.

Both Kline et al. [66] and Burnham et al. [67] follow similar procedures in the timed single-leg step-down test (Fig. 13.5a, b and Video 13.1). The subject stands on a 20-cm step with a digital scale (Ozeri ZB15, Ozeri USA, San Diego, CA) placed on the ground in front of the step. The stance (test) limb is positioned with the knee fully extended and the toes even with the front edge of the step. The opposite foot is held in front of the step while maintaining even height with the top of the step. Once the test begins, a single-leg step-down repetition consists of the subject flexing the stance knee, touching the scale with the left heel with ≤10% of their body weight and returning to the starting position. The number of successful repetitions completed in a 60-s period

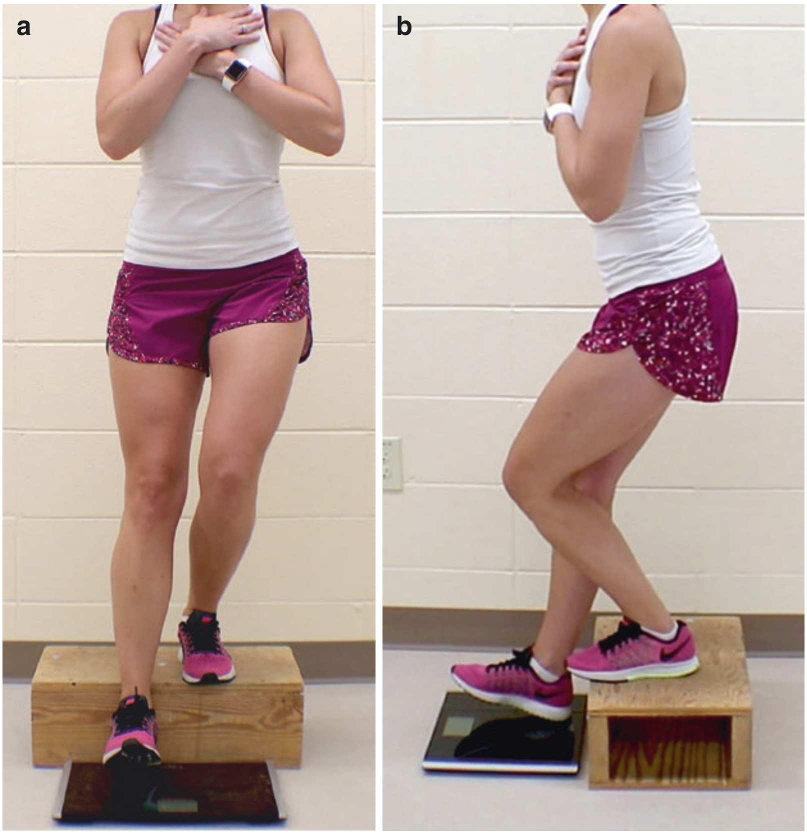

Fig. 13.5 Performance of the timed single-leg step-down test viewed (**a**) from the front and (**b**) from the side. Note that the patient touches the heel to the ground with ≤10% of their body weight, returns to the starting position, and performs as many repetitions as possible in 60 s

is recorded. A step down is not counted if the heel does not touch the scale; the subject places >10% body weight on the scale or does not fully bring the foot up parallel with the step. These studies highlight the potential of adding a timed single-leg step-down test to both return-to-play and pre-participation test battery for athletes. While informative, much work still remains to determine the full clinical utility and limitations of this dynamic assessment.

13.7 Clinical Implications

ACL injury is one of the most serious knee injuries incurred by the female athlete. Attention has focused on identifying the at-risk athlete, as well as developing and implementing prevention programs. A common theme of these programs has been to minimize knee valgus during dynamic activities by focusing on exercise designed to improve strength and neuromuscular control of not only the knee but also the core [8, 68].

Most prior works have used expensive equipment in a formal laboratory setting to determine that females perform dynamic activities with altered lower extremity kinematics, making them more vulnerable to a noncontact ACL injury. Based on the current available evidence, the single-leg squat represents a clinically useful tool capable of identifying increased knee valgus during dynamic movement. The quality of lower extremity movement during a single-leg squat can provide the clinician clinically important inferences regarding muscle function. This information is important as it will improve the clinician's ability to develop and implement treatment strategies that target a given athlete's impairments [56].

As outlined in the beginning of Sect. 13.4.2, optimal posture during the single-leg squat is a vertical trunk, level pelvis, externally rotated and abducted hip, and neutral knee position. However, the examiner should be aware of possible compensatory strategies. Although excessive contralateral pelvic drop indicates hip abductor weakness, athletes can compensate for this weakness through increased trunk lean over the stance limb. While this compensation essentially minimizes the amount of contralateral pelvic drop, it can adversely affect knee function. This compensatory strategy shifts the body's center of mass over the stance limb, which in turn transfers ground reaction forces more lateral to the knee joint [35]. This orientation can impart an excessive knee valgus moment, which is a common factor leading to ACL injury in the female athlete [11].

The incorrect performance on the single-leg step-down test is shown in Video 13.2. The hip internally rotates and adducts as the subject squats driving the knee into valgus and tibia externally rotates and foot pronates.

In addition to the single-leg squat test, other measurements exist that demonstrate gender differences in core strength and posture. The plank test is useful and may be done by observing the athlete's position or assessing time to fatigue. As shown in Fig. 13.6, the athlete is instructed to obtain the plank position, and a stick is placed posterior from the head to the heels. In the example shown in Fig. 13.6, the male demonstrates good ability to control his lumbar spine and pelvis, identified by the straight line from the lumbar spine which almost touches the stick. The natural position of the female is shown (middle photograph) with excessive lumbar lordosis, anterior rotation of the pelvis, and a significant distance between the stick and her spine. When the female was instructed to assume the proper plank position, she was able to do this for a short period of time as shown in the bottom photograph. Correlation of the plank test, single-leg mini-squat, and drop squat in future studies will help assess the high-risk individual and provide additions to return-to-play functional assessment testing.

In summary, an athlete's performance during a single-leg squat can provide clinically relevant information regarding core strength and neuromuscular activity. Together, this information can facilitate clinical decision-making for the development and implementation of ACL injury prevention programs. Figure 13.7 provides a summary of information gained during this screening test.

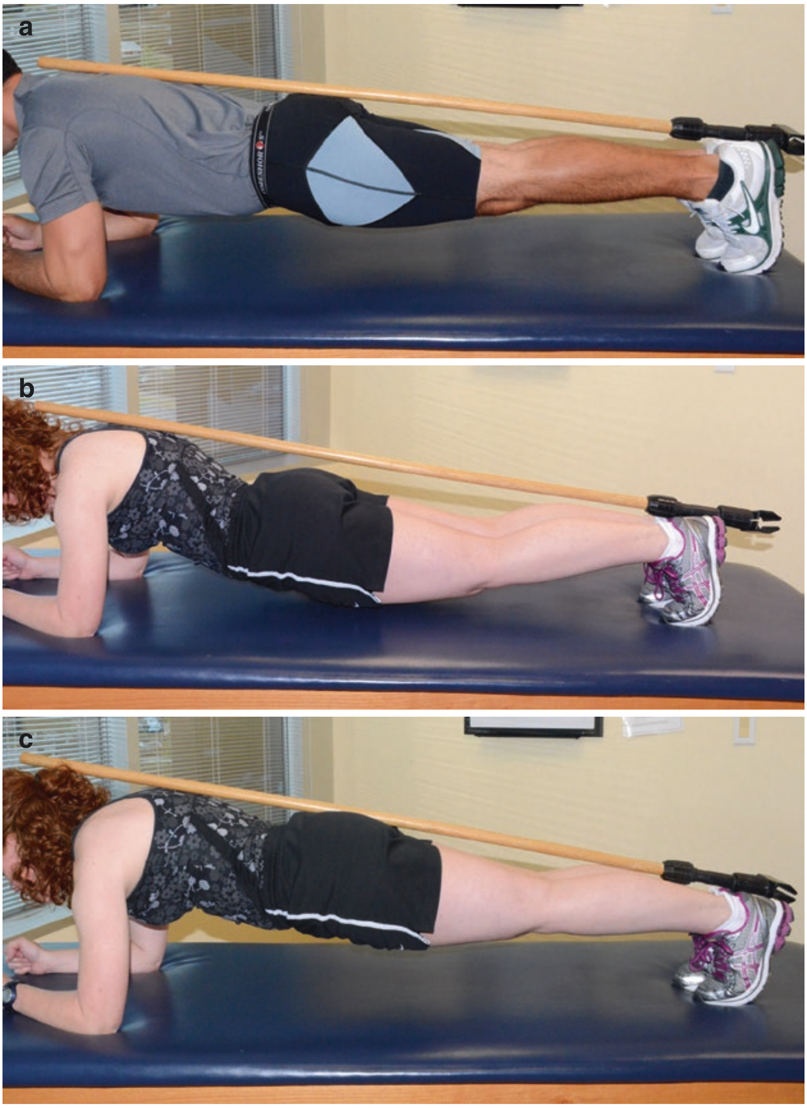

Fig. 13.6 Normal subjects performing the plank test. This test is measured by using a straight stick from the base of the skull to the feet. (**a**) The male has very little lumbar lordosis and an excellent plank position, with a posteriorly rotated pelvis and significantly greater contact with the stick than the female. (**b**) The female's plank position demonstrates excessive lumbar lordosis, forward pelvis position, and significantly less contact with the stick. (**c**) When prompted to obtain a normal plank position, the female is able to improve the position; however, there continues to be increased lumbar lordosis and anterior pelvic rotation compared to the male

Critical Points

- As shown in prior works that have examined lower extremity kinematics during running, cutting, and drop-landing tasks, females exhibit greater knee valgus than males during a single-leg squat.
- Clinicians should address not only trunk and hip strength but also neuromuscular control for the female athlete who demonstrates faulty lower extremity kinematics during a single-leg squat.

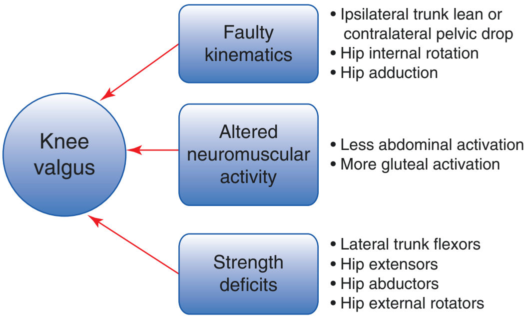

Fig. 13.7 Diagrammatic summary of factors contributing to knee valgus position. The three categories are kinematics, neuromuscular activity, and strength

Conclusion

ACL injury is one of the most serious and costly knee injuries. Seventy percent of ACL injuries occur via a noncontact mechanism, with females being at least 2.44 times more likely than males to incur injury in this manner [69]. Most data have shown that females perform demanding maneuvers with altered lower extremity mechanics that can lead to increased knee valgus loading. These findings have led to the development and implementation of prevention programs.

The success of prevention programs depends on the ability to identify the at-risk athlete using a simple, reliable, and valid screening tool. The single-leg squat represents such an assessment. Findings from the current literature have shown moderate correlations between altered trunk and hip strength and neuromuscular activity and increased knee valgus during this maneuver, especially in the female athlete. More importantly, researchers have seen similar faulty hip and knee mechanics in females during demanding tasks thought to make her more susceptible to ACL injury.

In summary, clinicians may use performance during a single-leg squat as an indicator of core and lower extremity function. Information gained from this assessment can help the clinician note impairments and, more importantly, prescribe individualized interventions. Therefore, we recommend the use of this assessment tool to screen females who may benefit from participation in an ACL injury prevention program.

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14 Effect of Fatigue and Gender on Lower Limb Neuromuscular Function

Sue Barber-Westin and Frank R. Noyes

Abstract

Approximately two-thirds of anterior cruciate ligament (ACL) tears are sustained under noncontact circumstances. Some investigators believe that fatigue may result in deleterious alterations in lower limb biomechanics that increase the risk of noncontact ACL injury. One important question is whether muscular fatigue uniformly alters lower limb biomechanics during cutting, pivoting, decelerating, or landing. A second question is whether fatigued female athletes have significant differences in knee and hip kinetics and kinematics and muscle activation patterns that may increase their risk of ACL injury. The issues are whether changes are required in ACL injury prevention training programs to account for fatigue-related lower limb biomechanical changes. We conducted a formal systematic review that involved 37 studies (485 female and 321 male athletes). The results indicated that published fatigue protocols did not uniformly produce alterations in lower limb biomechanical factors. There were few fatigue × gender interactions, and the question of whether the fatigued state places female athletes at greater risk of injury remains to be answered. There were no consistent data that demonstrated that the type of fatigue protocol (peripheral vs. general), athletic task selected (single-legged vs. double-legged), or task model (planned vs. reactive) strongly influenced changes in knee and hip kinematics and kinetics. Therefore, justification does not appear warranted for major changes in ACL injury prevention training programs to account for potential fatigue effects. The large variation in findings indicates the need for continued research in this area and refinement of fatigue protocols, athletic tasks selected for analysis, and methods of analysis.

14.1 Introduction

Muscle fatigue is typically defined as any exercise-induced reduction in the ability of a muscle to produce force or power [1]. Fatigue affects dynamic muscle control, lower limb movement patterns, and neuromuscular control. The decline in muscle force or power may be due to central factors (brain and/or spinal cord) or peripheral factors (muscle or peripheral nervous system) and is highly dependent on the capacity of the aerobic metabolic system [2]. Central factors include altered motor neuron firing rates, decreased neurotransmitter

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activity, altered excitability at the cortex, and inhibition of spinal excitability by afferent feedback [3]. Peripheral fatigue may arise as a result of impaired excitation-contraction coupling through changes in action potential propagation or calcium release or impairment of enzyme activity through local acidosis [4]. Although modern studies indicate that acidosis is not a major cause of fatigue, it is easily measured and is considered a good indicator of peripheral fatigue [2]. The basic hypothesis for the deleterious effects of fatigue is that muscles absorb less energy before reaching the degree of stretch that causes damage to structures such as ligaments. The multifactorial causes and methods for measuring fatigue have been discussed in detail elsewhere [2, 5, 6]. A recent study of high school athletes in the USA examined 19,676 lower extremity injuries sustained during nearly 17 million athlete exposures [7]. The majority of injuries occurred >1 h into practice and in the second half of games. The investigators concluded that fatigue may play a role in the higher incidence of injuries that occur later in practice and games; however, other factors that were not studied could contribute to the increased incidence.

At least two-thirds of ACL tears are sustained during noncontact circumstances when an athlete is cutting, pivoting, accelerating, decelerating, or landing from a jump [8–10]. Some investigations have hypothesized that fatigue may increase the risk of noncontact ACL injury [11–13] due in part to deleterious alterations that may occur in knee and hip flexion-extension, abduction-adduction, and internal-external rotation angles and moments, vertical ground reaction forces (vGRF), and muscular activation patterns in the lower extremity [14–16]. Factors that are believed to heighten the risk of noncontact ACL injury (regardless of gender or fatigue) include increased hip flexion, internal rotation, and adduction angles, reduced knee flexion and increased knee abduction angles, and increased external or internal tibial rotation. The issue has been raised by some investigators of the necessity to alter ACL injury prevention training programs to account for potential fatigue-related deleterious effects to these lower limb biomechanical factors.

Many different athletic tasks have been studied in neuromuscular fatigue studies, including single-leg motions (hopping, cutting, drop jump) and two-legged motions (vertical jump and drop jump). Santamaria et al. [15] systematically reviewed the effects of fatigue on single-leg landings in eight studies published from 2003 to 2008. Although fatigue appeared to affect some biomechanical variables, inconsistent findings precluded definitive clinical recommendations regarding ACL injury prevention training.

We reviewed all relevant studies published from January 2000 to June 1, 2016 in order to determine if fatigue protocols uniformly alter lower limb biomechanics during athletic tasks that are often associated with noncontact ACL injuries [17]. Secondly, we determined if fatigued female athletes have significant differences in knee and hip kinetics and kinematics and muscle activation patterns that may increase their risk of ACL injury compared with fatigued male athletes. The major goal of our review was to determine if changes are required in ACL injury prevention training programs to account for fatigue-related lower limb biomechanical changes.

14.2 Overview of Studies Reviewed

The articles selected for our review were original studies published in English from a peer-reviewed journal that used (1) athletically active subjects, (2) either a peripheral or general fatigue protocol, (3) at least one lower limb biomechanical (kinetic, kinematic) variable, and (4) at least one lower limb athletic task that involved landing from a hop or jump or cutting.

Our review [17] initially produced 806 potential articles; 37 were included in the final analysis [11, 12, 14, 16, 18–50].

There were 806 athletes in the 37 studies, including 485 females and 321 males whose mean age was 22.7 years. A comparison of female and male athletes was conducted in 11 studies [11, 13, 19, 21, 26, 31, 34, 39, 40, 43, 45]. There were 166 males (mean age, 23.7 years) and 162 females (mean age, 22.4 years) in these 11 investigations, and all were participating in a variety of school, league, or club sports.

A meta-analysis of the data analyzed was not performed because the studies were heterogeneous with regard to fatigue protocols, athletic tasks, methods of data collection, and biomechanical factors reported. Because of the heterogeneity of the studies, the methodological index for non-randomized studies (MINORS) instrument was used to rate the methodological quality of the investigations [51]. The MINORS score is reported as a percentage of the total available points [52]. The average MINORS score of the 37 studies was 83% (range, 67–92%).

14.3 Fatigue Protocols

Muscle fatigue protocols are either characterized as *general* (that impact the cardiovascular and motor systems) that are long in duration or *peripheral* (muscle specific, such as quadriceps or hamstrings) that are relatively short in duration. The goal of general fatigue protocols is to simulate realistic game or match situations [12] because fatigue effects occur cumulatively throughout a practice or game [34]. These protocols use gradual bouts of submaximal activity to cause a reduction in the level of voluntary muscle activation. Impairment occurs at sites proximal to the neuromuscular junction (spinal and supraspinal levels) that promote inadequate drive to the working muscles [35]. In contrast, peripheral fatigue leads to a reduction in the force-generating capacity of the muscle at or distal to the level of the neuromuscular junction [35]. It is caused mainly by metabolic factors or muscle damage if eccentric contractions are prominent and does not encompass changes in overall neuromuscular control. Peripheral protocols target either individual muscles or the entire lower extremity.

In our review, general fatigue protocols were used in 20 studies and peripheral in 17. The peripheral protocols targeted the entire lower extremity in five studies, the quadriceps in five studies, the quadriceps and hamstrings in two studies, the hip abductors in two studies, the plantar flexors in two studies, and the hip extensors in one study. The general fatigue protocols consisted of (1) a series of different tasks (such as vertical jumps, squats, agility drills, drop jumps) either done until exhaustion or for a specified time period, (2) a running endurance test to exhaustion, (3) an endurance test over a specified time, or (4) a 45-min soccer match. Indicators of fatigue such as heart rate or perceived exertion scales were used in 16 studies.

14.4 Lower Limb Athletic Tasks Studied

Twenty-one different lower limb athletic tasks were studied; 13 were single-leg activities, and 8 were two-legged activities (Table 14.1). The majority of investigations (89%) studied just one

Table 14.1 Athletic tasks analyzed

Athletic task	Studies (*n*)
Single-legged activities:	
Single-leg drop jump	9
Single-leg hop for distance	5
Lateral side cut	4
45° sidestep cut	4
Single-leg vertical jump	2
Single-leg triple hop for distance	1
Single-leg crossover hop for distance	1
Single-leg timed hop	1
Single-leg square hop	1
Crossover task	1
90° sidestep cut	1
Side-cut (angle unknown)	1
Single-leg stop jump	1
Single-leg up-down hop	1
Two-legged activities:	
Two-legged drop jump	5
Running stop jump	2
Two-legged hopping in place	1
Two-legged vertical jump	1
Straight run after landing from jump	1
Stop jump, forward lean	1
Stop jump, vertical lean	1
Stop jump, backward lean	1
Number of tasks per study:	
One	32
Two	3
Three	1
Four	1

From Barber-Westin and Noyes [17]

task. A planned (or anticipated) athletic task model was used in 28 studies, a reactive (or unanticipated) task model was used in seven studies, and both planned and reactive task models were used in two studies. Planned athletic tasks involved no decision-making on the part of the subject and most commonly involved a drop jump or single-leg hop. Reactive tasks were typically used in studies that involved cutting. For instance, one study [12] used a random light stimulus that was automatically triggered with a light beam which appeared approximately 350 ms before initial contact (IC). The display directed the subject to move in the desired lateral direction after landing from a forward jump.

14.5 Overall Effect of Fatigue on Lower Limb Biomechanics and Muscle Activation Patterns

There were no consistent results among the 37 investigations regarding the effects of fatigue on knee or hip joint angles (Figs. 14.1 and 14.2) or moments (Figs. 14.3 and 14.4). There were no

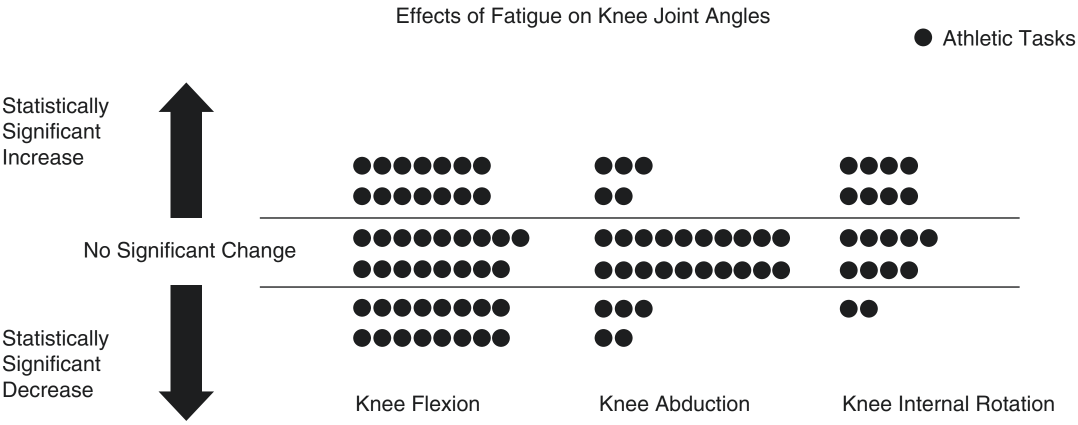

Fig. 14.1 There were no uniform effects of fatigue on knee joint angles. Each dot indicates the result for athletic tasks for either the entire cohort or for each subgroup when comparisons were performed (such as gender, fatigue protocol, or different tasks) within a study. Knee flexion, 47 task analyses in 28 studies; knee abduction, 30 task analyses in 23 studies; and knee internal rotation, 19 task analyses in 12 studies. From Barber-Westin and Noyes [17]

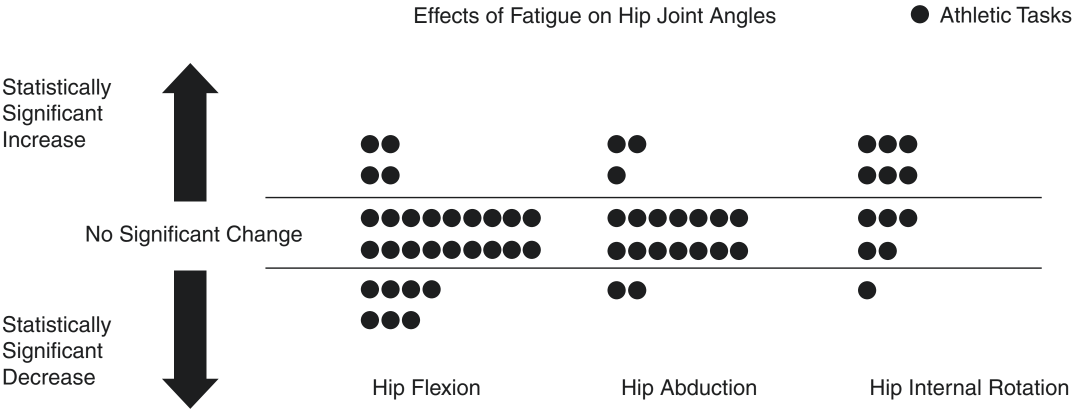

Fig. 14.2 There were no uniform effects of fatigue on hip joint angles. Each dot indicates the result for athletic tasks for either the entire cohort or for each subgroup when comparisons were performed (such as gender, fatigue protocol, or different tasks) within a study. Hip flexion, 29 task analyses in 25 studies; hip abduction, 19 task analyses in 15 studies; and hip internal rotation, 12 task analyses in 11 studies. From Barber-Westin and Noyes [17]

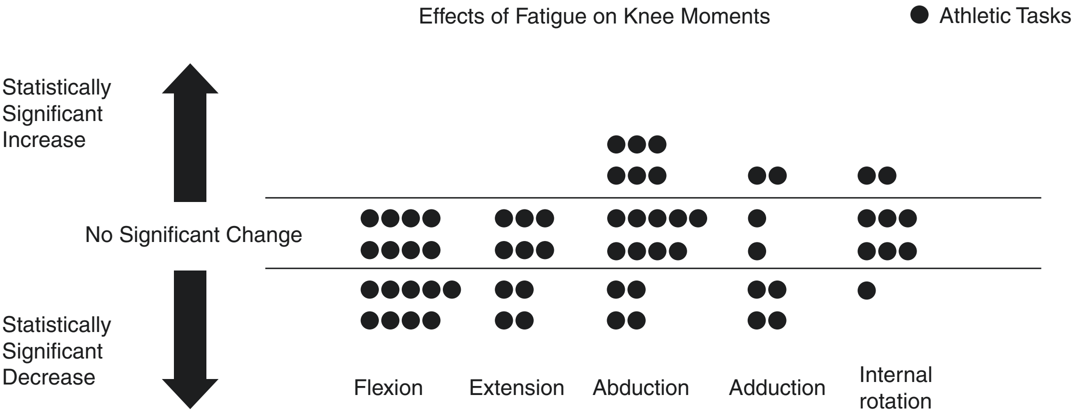

Fig. 14.3 There were no uniform effects of fatigue on knee moments. Each dot indicates the result for athletic tasks for either the entire cohort or for each subgroup when comparisons were performed (such as gender, fatigue protocol, or different tasks) within a study. Flexion, 17 task analyses in 11 studies; extension, 10 task analyses in 7 studies; abduction, 19 task analyses in 11 studies; adduction, 8 task analyses in 7 studies; and internal rotation, 9 task analyses in 6 studies. From Barber-Westin and Noyes [17]

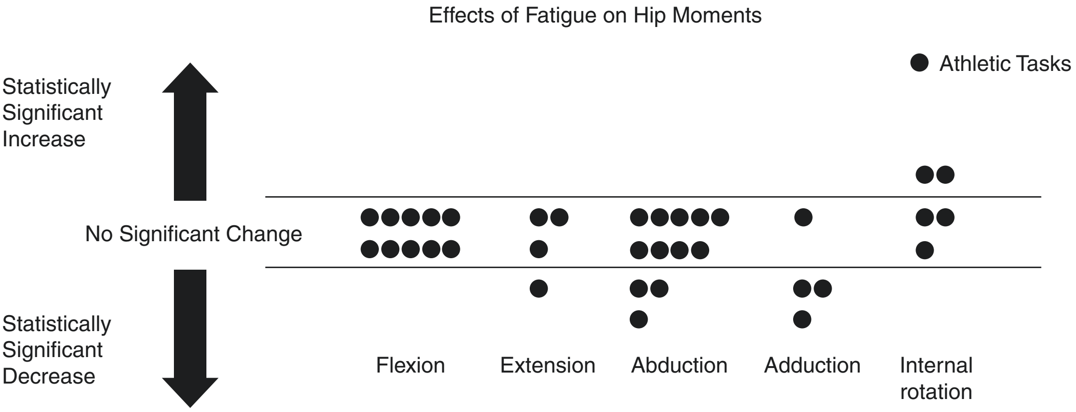

Fig. 14.4 There were few effects of fatigue on hip moments. Each dot indicates the result for athletic tasks for either the entire cohort or for each subgroup when comparisons were performed (such as gender, fatigue protocol, or different tasks) within a study. Flexion, 10 task analyses in 9 studies; extension, 4 task analyses in 4 studies; abduction, 12 task analyses in 6 studies; adduction, 4 task analyses in 4 studies; and internal rotation, 9 task analyses in 6 studies. From Barber-Westin and Noyes [17]

uniform differences between peripheral and general fatigue protocols (Table 14.2) or between single-legged and two-legged athletic tasks (Table 14.3) regarding post-fatigue effects on any lower limb biomechanical variable.

There were no consistent results between planned and reactive athletic tasks regarding post-fatigue effects on lower limb biomechanical variables (Table 14.4). The only exception was knee flexion, which was significantly decreased after fatigue in seven of eight reactive tasks. In comparison, no consistency was found after fatigue for changes in knee flexion when planned athletic task models were selected for analysis.

Nineteen studies reported the effects of fatigue on vGRF. Only two studies [19, 40] found significant increases in landing forces; however, one of these [40] reported a small effect size (ES) (0.14), while the other reported a mean increase in vGRF from 2202.5 ± 536.29 N to 2537.86 ± 469.66 N ($P = 0.002$) [19].

Table 14.2 Effect of type of fatigue protocol on changes in lower limb biomechanics

		Post-fatigue statistically significant effects		
	Type of fatigue protocol	No change (no.)	Increased (no.)	Decreased (no.)
Knee angles				
Flexion	Peripheral	7	13	5
	General	10	1	11
Abduction	Peripheral	13	3	2
	General	7	4	3
Internal rotation	Peripheral	7	2	0
	General	2	8	0
Knee moments				
Flexion	Peripheral	6	0	4
	General	4	0	3
Extension	Peripheral	2	0	3
	General	2	0	1
Abduction	Peripheral	6	2	3
	General	3	4	1
Adduction	Peripheral	0	2	1
	General	2	0	3
Internal rotation	Peripheral	5	0	0
	General	3	2	0
Hip angles				
Flexion	Peripheral	12	4	2
	General	9	0	5
Abduction	Peripheral	8	3	0
	General	7	0	2
Internal rotation	Peripheral	2	4	0
	General	5	2	1
Hip moments				
Flexion	Peripheral	6	0	0
	General	6	0	0
Extension	Peripheral	4	0	1
	General	0	0	0
Abduction	Peripheral	6	0	2
	General	1	0	1
Adduction	Peripheral	0	0	2
	General	3	0	1
Internal rotation	Peripheral	4	1	0
	General	4	1	0
Landing forces[a]	Peripheral	7	0	5
	General	7	2	1

[a] One single-leg landing task study reported a decrease in landing forces after a quadriceps fatigue protocol but no change after a hamstrings fatigue protocol. Another single-leg landing task study reported no change in landing forces after either a general or peripheral fatigue protocol

From Barber-Westin and Noyes [17]

Table 14.3 Effect of type of athletic task on changes in lower limb biomechanics

		Post-fatigue statistically significant effects		
	Type of athletic task	No change (no.)	Increased (no.)	Decreased (no.)
Knee angles				
Flexion	Single-legged	11	11	9
	Two-legged	6	3	6
Abduction	Single-legged	16	2	4
	Two-legged	4	3	1
Internal rotation	Single-legged	7	4	2
	Two-legged	2	4	0
Knee moments				
Flexion	Single-legged	4	0	9
	Two-legged	4	0	0
Extension	Single-legged	3	0	4
	Two-legged	3	0	0
Abduction	Single-legged	7	3	4
	Two-legged	2	3	0
Adduction	Single-legged	2	2	3
	Two-legged	0	0	1
Internal rotation	Single-legged	6	0	1
	Two-legged	9	2	0
Landing forces	Single-legged	10	1	2
	Two-legged	3	1	1

From Barber-Westin and Noyes [17]

Table 14.4 Effect of athletic task model on changes in lower limb biomechanics

		Post-fatigue statistically significant effects		
	Athletic task model	No change (no.)	Increased (no.)	Decreased (no.)
Knee angles				
Flexion	Planned	18	14	10
	Reactive	1	0	7
Abduction	Planned	21	7	22
	Reactive	1	2	3
Internal rotation	Planned	8	5	0
	Reactive	2	4	0
Knee moments				
Flexion	Planned	6	0	7
	Reactive	2	0	3
Extension	Planned	4	0	3
	Reactive	0	0	1
Abduction	Planned	3	4	2
	Reactive	2	1	2
Adduction	Planned	1	2	3
	Reactive	1	0	1
Internal rotation	Planned	9	2	0
	Reactive	1	0	0
Hip angles				
Flexion	Planned	22	4	3
	Reactive	2	0	5
Abduction	Planned	15	3	0
	Reactive	3	0	2

(continued)

Table 14.4 (continued)

		Post-fatigue statistically significant effects		
	Athletic task model	No change (no.)	Increased (no.)	Decreased (no.)
Internal rotation	Planned	7	9	0
	Reactive	0	2	1
Hip moments				
Flexion	Planned	13	0	0
	Reactive	3	0	0
Extension	Planned	4	0	0
	Reactive	0	0	1
Abduction	Planned	6	0	2
	Reactive	1	0	1
Adduction	Planned	2	0	5
	Reactive	1	0	1
Internal rotation	Planned	7	5	0
	Reactive	0	1	0
Landing forces*	Planned	10	2	6
	Reactive	4	0	1

From Barber-Westin and Noyes [17]

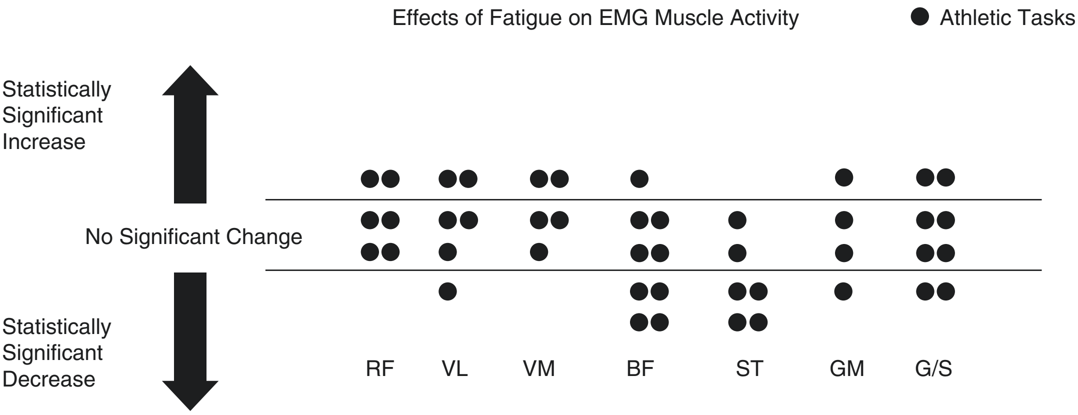

Fig. 14.5 There were no uniform effects of fatigue on EMG muscle activation patterns. *RF* rectus femoris, *VL* vastus lateralis, *VM* vastus medialis, *BF* biceps femoris, *ST* semitendinosus, *GM* gluteus medius, *G/S* gastrocnemius-soleus. Each dot indicates the result for athletic tasks for either the entire cohort or for each subgroup when comparisons were performed (such as gender, fatigue protocol, or different tasks) within a study. RF, 6 task analyses in 6 studies; VL, 6 task analyses in 5 studies; VM, 5 task analyses in 5 studies; BF, 9 task analyses in 7 studies; ST, 6 task analyses in 5 studies; GM, 4 task analyses in 4 studies; G/S, 8 task analyses in 6 studies. From Barber-Westin and Noyes [17]

Nine studies reported no significant changes in ankle dorsiflexion after fatigue [12, 18, 25, 34, 37, 44, 46–48], two reported increases in dorsiflexion [13, 33], one reported a decrease in dorsiflexion [23], and one reported an increase in plantar flexion [19]. Four studies reported no changes in inversion-eversion angles following fatigue protocols [25, 34, 44, 46].

There was no consistency regarding the effects of fatigue protocols on surface electromyography (EMG) muscle activation patterns (Fig. 14.5). Six studies used a single-leg task, four of which studied quadriceps and hamstrings activity [29, 37, 38, 50]. Two reported no changes in quadriceps activity [38, 50], one study reported an increase after a hamstrings fatiguing protocol (but no change after a quadriceps fatiguing protocol) [29], and one reported an increase after a quadriceps fatiguing protocol [37]. Four studies [26, 28, 39, 40] used a double-legged task, one of which only reported gluteus maximus activity [28]. Two of these reported no change in quadriceps activity [26, 39], while one reported increased activity [40]. For the hamstrings, decreased activity was reported in two investigations [26, 39], while no change was found in another [40]. Gastrocnemius-soleus activity was reported in a total of six studies [26, 29, 37, 39, 40, 50], three of which found no change after fatigue [37, 40, 50].

14.6 Effect of Gender and Fatigue on Lower Limb Biomechanics and Muscle Activation Patterns

General fatigue protocols were used in six studies, and peripheral protocols were selected in five studies that performed gender comparisons. A single-leg drop jump was used in three studies, a double-legged drop jump was done in three, stop-jump tasks were used in two, single-leg hops were done in two, and a double-legged hop was done in one. All of these athletic tasks were preplanned.

There were few gender × fatigue effects reported in these investigations (Table 14.5). Two studies [13, 39] reported gender-related changes in knee flexion after fatigue; however, the findings were in direct contrast. Kernozek et al. [13] reported that although men increased maximum knee flexion on a single-leg drop jump after fatigue (mean, 7°, $P < 0.05$), there were no significant changes in women. Padua et al. [39] found that while women increased knee flexion at IC after fatigue on a two-legged hop test (mean, 4.8°, $P = 0.03$), there were no significant changes in knee flexion in men. Neither of these studies provided ES.

Two studies reported a significant increase in knee abduction (valgus) moments in women post-fatigue [21, 34]. McLean et al. [34] reported a significant increase in peak abduction moments on a two-legged drop jump from pre-fatigue to post-fatigue (0.34 and 0.18 N m kg^{-1} m^{-1}, respec-

Table 14.5 Effects of gender and fatigue on biomechanical variables

Study	Athletic task, type of fatigue protocol, subjects	Gender differences post-fatigue	Gender differences, regardless of fatigue state[a] Findings women compared with men
Liederbach et al. [31]	Single-leg drop jump, peripheral, 40 women, 40 men	None	Greater pk knee abduction (4.9° and 2.5°, respectively, $P < 0.05$, ES = NA)
Brazen et al. [19]	Single-leg drop jump, general, 12 women, 12 men	None	None
Kernozek et al. [13]	Single-leg drop jump, peripheral, 14 women, 16 men	Knee flexion: men increased pre-post-fatigue (67°–74°, $P < 0.05$, ES = NA); women no change	Greater vGRF (3.84 vs. 3.52% BW, $P = 0.002$) Greater max hip flexion (40.7° vs. 26.6°, $P = 0.001$) Greater max knee abduction (3.86° vs. 0.97°, $P = 0.009$) Smaller max knee adduction (3.86° vs. 8.51°, $P < 0.05$) All ES = NA
Gehring et al. [26]	Two-legged drop jump, peripheral, 13 women, 13 men	None	Greater max knee flexion (87.6° vs. 71.8°, $P = 0.001$) Greater IC knee abduction (−3.1° vs. -6.7°, $P < 0.05$) Greater max knee abduction (4.0° vs. -6.1°, $P = 0.007$) Delayed onset vastus lateralis activity prior to IC (39 vs. 51 ms, $P = 0.02$) Delayed onset biceps femoris activity prior to IC (84 vs. 97 ms, $P < 0.05$) All ES = NA

(continued)

Table 14.5 (continued)

Study	Athletic task, type of fatigue protocol, subjects	Gender differences post-fatigue	Gender differences, regardless of fatigue state[a] Findings women compared with men
Pappas et al. [40]	Two-legged drop jump, general, 16 women, 16 men	None	Greater pk knee abduction (14.9° vs. 6.0°, $P < 0.001$; ES = 1.18) Greater pk vGRF (5.3 vs. 3.9 BW, $P = 0.003$; ES = 1.08)
McLean et al. [34]	Two-legged drop jump, general, 10 women, 10 men	Knee abduction moments: women greater increase pre-post-fatigue (0.21 vs. 0.08 N•m•kg^{-1} m^{-1}, $P = 0.002$) All ES = NA	Greater pk knee abduction (3.4° vs. 1.6°, $P = 0.001$) Greater pk knee IR (12.5° vs. 4.9°, $P = 0.001$) Greater IC ankle plantar flexion (26.6° vs. 19.6°, $P < 0.001$) Greater ankle supination (14.5° vs. 9.6°, $P < 0.001$) Greater knee IR moments (−0.11 vs. -0.08 N•m•kg^{-1} m^{-1}, $P < 0.05$) Greater pk ankle dorsiflexion moments (−1.00 vs. −1.09 N•m•kg^{-1} m^{-1}, $P < 0.05$) All ES = NA
Benjaminse et al. [11]	Stop jump, general, 15 women, 15 men	None	None
Chappell et al. [21]	Stop jumps (×3), general, 10 women, 10 men	Varus/valgus moment: women increased valgus pre-post-fatigue (0.026–0.051 BWxht, $P < 0.05$) whereas men decreased varus pre-post-fatigue (0.030–0.017 BWxht, $P < 0.05$). All ES = NA	Greater pk knee flexion (26.3° vs. 33.4°, $P = 0.001$) Greater pk proximal tibial anterior shear force (0.35 vs. 0.18 × BW, $P = 0.001$) Greater knee extension moments (0.123 vs. 0.024 BW × ht., $P = 0.001$) All ES = NA
Ros et al. [43]	Single-leg hop and single-leg square hop, general, 10 women, 10 men	None	None
Thomas et al. [45]	Single-leg hop, peripheral, 12 women, 13 men	None	Greater pk vGRF knee flexion (28.1° vs. 22.9°, $P < 0.05$) Greater IC hip flexion (31.5° vs. 26.0°, $P < 0.05$) Greater pk vGRF hip flexion (33.4° vs. 27.6°, $P < 0.05$) Smaller IC hip abduction (−3.8° vs. −8.5°, $P < 0.05$) Smaller pk vGRF hip abduction (−1.1° and −6.4°, $P < 0.05$) All ES = NA
Padua et al. [39]	Two-legged hopping, peripheral, 10 women, 11 men	Knee flexion angle: women increased at IC pre-post-fatigue (mean 4.8°, $P = 0.03$, ES = NA); men no change	Greater quadriceps pk EMG activity 50 mc before IC and 50 ms after IC (45%, $P = 0.03$) Greater quadriceps: hamstrings coactivation ratio (1.9 vs. 1.1, $P < 0.05$) All ES = NA

[a] Examples shown are pre-fatigue values (mean women vs. mean men)

BW body weight, *EMG* electromyography, *ES* effect size, *Ht* height, *IC* initial contact, *IR* internal rotation, *ms* milliseconds, *NA* not available, *pk* peak, *vGRF* vertical ground reaction force tively, $P < 0.05$). In addition, women had a significantly greater increase in abduction moments compared with men after fatigue (0.21 and 0.08 N m kg^{-1} m^{-1}, respectively, $P = 0.002$). Chappell et al. [21] found that while women had a significant increase in knee abduction moments on the landing phase of stop-jump tasks between pre- and post-fatigue states (overall mean, 0.026 and 0.051 body weight × height, respectively, $P < 0.05$), men had a significant decrease in adduction moments between pre- and post-fatigue states (0.030 and 0.017 body weight × height, respectively, $P < 0.05$). Neither of these studies provided ES.

There were many findings related to gender differences in these 11 studies that were evident regardless of the fatigue state (Table 14.5). These well-known neuromuscular differences are described in detail in Chaps. 6, 7, 9, and 11.

14.7 Discussion

Our review found that published fatigue protocols did not uniformly produce alterations in lower limb biomechanical factors that are believed to heighten the risk of noncontact ACL injuries. There were few fatigue × gender interactions, and the question of whether the fatigued state places female athletes at even greater risk of injury (compared with unfatigued females or males) remains to be answered. There were no consistent data that demonstrated that the type of fatigue protocol (peripheral versus general), athletic task selected (single-legged versus double-legged), or task model (planned versus reactive) produced clinically relevant changes in knee and hip kinematics and kinetics. Therefore, justification does not appear warranted at present for major changes in ACL injury prevention training programs to account for potential fatigue effects.

Because the 37 studies we reviewed were heterogeneous with regard to fatigue protocols used, athletic tasks selected, data collection methods, and biomechanical factors reported, a meta-analysis of the data was not performed. Our review found several methodological problems that should be addressed in future investigations. For instance, several studies did not include a direct measure of muscular fatigue (such as loss of muscle power) to indicate when the protocol should end and thus appeared to assume that a fatigued state had been reached by all subjects [23, 34, 40, 44, 49, 50]. The protocols were either based on a certain amount of repetitions or time in which athletic tasks were performed. Using time alone as an indicator of fatigue is problematic because athletes have inherent sets of parameters that involve complex central and metabolic factors. Potential between subject variations in cardiovascular and muscular endurance may confound biomechanical findings. In addition, studies have shown that women and men exhibit different fatigue levels and that the magnitude of this gender difference is specific to the task performed and the muscle groups involved [53].

The effects of fatigue on cutting tasks were studied in 11 investigations. Three studies that used general fatigue protocols and a planned athletic task model found no significant post-fatigue change in knee flexion [12, 44, 50]. However, four studies reported significant decreases in knee flexion that ranged from 3° to 10°, and the majority of these used a reactive task model [14, 22, 32, 35]. There was no significant change in landing forces in the three studies that provided these data [32, 35, 50]. Regarding alterations in hip angles, only three studies reported decreased hip flexion after fatigue (range, 3.6°–8.4°); all of these used general fatigue protocols and reactive athletic tasks [12, 22, 32]. Six other studies found no significant change in hip flexion after fatigue [14, 27, 35, 44, 46, 50]. Four studies reported increases in hip internal rotation that ranged from 0.8° to 6.9° after both planned and reactive athletic tasks and either a general or peripheral fatigue protocol [12, 32, 35, 46]. Only three studies reported results related to hip abduction angles, which were increased in two [22, 27] and not significantly changed in one [14].

The effects of fatigue on drop-jump tasks (two-legged and single-legged) were analyzed in 14 investigations. Post-fatigue effects on knee angles were analyzed in all of these studies, but the effects on hip angles were only assessed in eight studies. Peripheral fatigue protocols were used in eight studies and all, but two [20, 41] of these reported significant increases in knee flexion after fatigue (range, 2.4°–10.7°) [13, 25, 26, 29, 31, 33]. General fatigue protocols were used in six studies, of which only one reported a significant increase in knee flexion (6.5°) [19], while the others found no significant changes. Only two studies reported increases in knee abduction angles that ranged from <2° [20] to 6.8° [34], and only two studies reported increases in knee internal rotation angles that ranged from 3.6° [47] to 7.28° [34]. The remaining studies either found no increases or did not study these factors. Five studies [31, 33, 34, 41, 47] reported no post-fatigue changes in hip flexion, and three reported increases that ranged from 3.4° to 8.9° [13, 25, 29]. Significant decreases in landing forces were noted in four studies [25, 26, 29, 33], significant increases were found in two studies [19, 40], and no change was reported in three studies [13, 20, 41].

Five studies ascertained the effect of fatigue on hop tests; two used general fatigue protocols [43, 49], and three used peripheral protocols [18, 37, 45]. Neither general fatigue model resulted in significant decreases in hop distance immediately following conclusion of the fatigue protocol. For instance, Ros et al. [43] reported that although the mean heart rate was 180 beats/minute in 10 women after an intermittent endurance test, hop distance only decreased a mean of 2 cm. Peripheral fatigue protocols had varying results related to lower limb biomechanics. One study reported a mean increase in hip internal rotation of 3.3° at IC from a single-leg hop, but no significant differences in hip extension or abduction [45]. In this study, knee external rotation increased a mean of 2.7°, and knee extension increased a mean of 5.4°. Another investigation reported a significant increase in mean knee flexion of 14° and a significant decrease in hip flexion of 5.6° on landing from a single-leg hop [37].

Effect size measures the magnitude of the effects of treatment and is especially important in studies with small sample sizes [54]. One problem discovered in this review was that only eight studies (22%) provided ES in addition to *P* values. We believe some of the statistically significant findings ($P < 0.05$) have limited clinical relevance. For instance, one study reported a mean increase in knee flexion after a peripheral fatigue protocol of 4.8° ($P < 0.05$) on landing from a two-legged hop in ten women [39]. The clinical relevance as related to an increase in the risk of sustaining a noncontact ACL injury due to small changes in knee flexion is questionable. Only one study reported large post-fatigue ES on a drop-jump task (mean increase knee flexion 5.8°, ES 2.32; mean increase hip flexion 3.4°, ES 1.49) [25].

Another concern was that only 20 studies (54%) conducted a prospective power calculation of the sample size required to discern a detectable difference (95% confidence interval). Several of these did not provide the expected (or hypothesized) mean ± standard deviation of relevant variables required to achieve a sufficient sample size [13, 27, 31, 40, 47]. Patrek et al. [41] selected a change of greater than 3° of hip or knee frontal plane flexion and abduction in their sample size determination, based on data from a prior study that showed this magnitude represented a moderate to large ES (0.7). Sanna et al. [44] selected 2° difference in frontal plane hip and knee kinematics, based on pilot data, to determine their sample size. The determination of which variables are the most relevant to the noncontact ACL injury dilemma and the magnitude of change in these variables that represents a true risk indicator requires clarification in future studies.

The majority of studies reported means ± standard deviations only; ranges were frequently not provided nor were the percent of subjects whose post-fatigue results placed them in a (hypothesized) heightened risk category for a noncontact ACL injury. Reporting the percent of subjects that had significant or clinically relevant changes for each biomechanical factor analyzed is recommended. In addition, the development of a biomechanical profile for each athlete would also be helpful in future studies. The use of tests such as the drop jump, knee arthrometer testing, and isokinetic strength allows identification of patients that may have a higher-risk profile for ACL injury [55–59]. Then, the effects of either general or peripheral fatigue protocols, reactive or planned athletic tasks, and various athletic tasks (cutting, landing, etc.) could be analyzed according to the biomechanical profile.

It would be advantageous for future studies to uniformly incorporate specific fatigue indicators, such as direct measurement of heart rate and muscular power. Consensus needs to be reached of these measures in terms of when fatigue has been reached, such as the percent of maximum vertical jump height or peak isokinetic torque compared with baseline values. For instance, the studies in this review that used vertical jump height selected ranges from 10% of baseline [22, 31] to 20% of baseline [47] to indicate fatigue had been achieved without providing a rationale for these values.

Conclusions

The risk factors believed by many investigators that heighten the risk of a noncontact ACL injury include decreased hip and knee flexion angles, increased hip internal rotation, increased hip adduction angles, increased knee abduction angles, increased external or internal tibial rotation, increased external abduction and flexion moments, increased quadriceps forces, and reduced hamstring activity [60, 61]. Our review found that published fatigue protocols did not uniformly produce alterations in these lower limb biomechanical factors. There were few fatigue × gender interactions, and the question of whether the fatigued state places female athletes at even greater risk of injury remains to be answered. There were no consistent data that demonstrated that the type of fatigue protocol (peripheral versus general), athletic task selected (single-legged versus double-legged), or task model (planned versus reactive) produced clinically relevant changes in knee and hip kinematics and kinetics. Therefore, justification does not appear warranted for major changes in ACL injury prevention training programs to account for potential fatigue effects. The large variation in findings indicate the need for continued research in this area and refinement of fatigue protocols, athletic tasks selected for analysis, and methods of analysis.

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15

Multivariate Analyses of Risk Factors for Noncontact Anterior Cruciate Ligament Injuries

Morgan Hadley and Bruce Beynnon

Abstract

This chapter reviews investigations that have used multivariate approaches to determine the risk factors associated with increased risk of suffering ACL injury. One study assessed the effect of sport, level of play, and gender. Other studies analyzed the effect of demographic characteristics, joint laxity, lower extremity alignment, and strength. Several investigations have assessed the effect of knee geometric characteristics in increasing the incidence of noncontact ACL injury.

15.1 Introduction

Severe ligament injury, such as that associated with disruption of the anterior cruciate ligament (ACL), is associated with considerable joint trauma and is implicated as the inciting event for short-[1] and long-term [2] changes to the articular structures of the knee and increased risk for the onset and progression of post-traumatic osteoarthritis (PTOA) regardless of whether an individual chooses nonsurgical or surgical treatment [3]. These observations have focused research efforts on understanding the mechanisms and risk factors that predispose an individual to suffering severe joint trauma. A majority of the prognostic studies for ACL injury have focused on potential risk factors for injury in isolation (e.g., have used univariate analysis); however, it is clear that multiple risk factors act in combination to influence the risk of ACL injury. Of recent interest have been prognostic investigations that have used multivariate analysis to determine the combination of independent risk factors that are associated with increased risk of suffering ACL injury as such risk models are more predictive of risk than individual variables. Multivariate risk models are important for the development of injury prevention programs that address the combined influence of a selection of factors rather than focusing on one aspect of susceptibility to ACL injury in isolation. Such models are needed for identifying those who are at increased risk so that they can be counseled about their chances of sustaining an ACL injury and be offered interventions for injury prevention. This is critical because at the current point in time, the efficacy of ACL injury prevention programs appears to be emerging; however, little is known

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about how to identify those at greatest risk, and consequently we do not know at whom to target the programs. Development of approaches to identify those at greatest risk of suffering ACL injury is important because it will allow valuable resources to be directed at these individuals, rather than intervening on the overall population at risk with the hope of reducing the risk of injury in the minority that are most likely to suffer this trauma. This chapter will review investigations that have used multivariate approaches to determine the risk factors associated with increased risk of suffering ACL injury.

15.2 Effect of Sport, Level of Play, and Gender on Risk of ACL Injury

A prospective cohort study of first-time noncontact complete ACL injury in competitive athletes from 26 institutions (8 colleges and 18 high schools) was conducted over a 4-year time interval [4]. Noncontact injury was defined as a complete disruption of the ACL in an individual with no previous injury to either ACL that was produced as a result of participating in a high school or college game or practice and did not involve direct contact to the knee from external forces such as those produced by other athletes or equipment. An athlete exposure (AE) was defined as one athlete's participation in a practice or game and was determined retrospectively for all teams in the study.

The incidence rates (IRs) of ACL injury observed in high school and collegiate athletes participating in specific sports are presented in Table 15.1. The high school athletes suffered 53 noncontact ACL injuries with 873,057 exposures across all sports studied (IR = 0.061 per 1000 AE), while the collegiate athletes suffered 48 ACL injuries with 320,719 exposures (IR = 0.150 per 1000 AE) (Table 15.2). In general, the IRs were higher for females compared with males and for collegiate athletes compared with high school athletes. These differences were evident when IRs were grouped across participant gender, level of play, and type of sport and were confirmed by the adjusted relative risk estimates (Table 15.2).

Athlete gender, type of sport, and level of play were independently associated with the risk of suffering a first-time noncontact ACL injury. When controlling for ACL injury, the relative risk

Table 15.1 Rates of first-time noncontact anterior cruciate ligament injury among athletes participating in college and high school sports

	College				High school			
Sport	Athlete exposures	Number of ACL injuries	Injury rate per 1000 athlete exposures	95% CI	Athlete exposures	Number of ACL injuries	Injury rate per 1000 athlete exposures	95% CI
Male								
Soccer	30,241	6	0.198	0.073–0.432	117,140	3	0.026	0.006–0.075
Basketball	38,927	2	0.051	0.006–0.186	108,622	4	0.037	0.010–0.094
Lacrosse	71,731	6	0.084	0.031–0.182	121,583	7	0.058	0.023–0.119
Football	18,417	3	0.163	0.035–0.476	144,233	8	0.055	0.024–0.109
Rugby	17,886	3	0.168	0.036–0.490				
Female								
Soccer	28,115	11	0.391	0.195–0.700	114,077	15	0.131	0.074–0.217
Basketball	34,882	5	0.143	0.047–0.335	98,296	6	0.061	0.022–0.133
Lacrosse	37,567	4	0.106	0.029–0.273	86,160	6	0.070	0.026–0.152
Field hockey	25,993	1	0.038	0.001–0.214	82,946	4	0.048	0.013–0.123
Rugby	14,723	6	0.408	0.150–0.887	NA	NA	NA	NA
Volleyball	2237	1	0.447	0.011–2.491	NA	NA	NA	NA

NA not applicable
From Beynnon et al. [4]

Table 15.2 First-time noncontact anterior cruciate ligament injury rates and relative risks associated with gender, level of play, and sport

	Athlete exposures	Number of ACL injuries	Injury rate per 1000 athlete exposures	95% CI	Relative risk (adjusted)	95% CI
Male	668,780	42	0.063	0.045–0.085	1.00	
Female	524,996	59	0.112	0.086–0.145	2.10	1.34–3.27
High school	873,057	53	0.061	0.045–0.079	1.00	
Collegiate	320,719	48	0.150	0.110–0.198	2.38	1.55–3.64
Soccer	289,573	35	0.121	0.084–0.168	1.77	1.04–3.01
Basketball	280,727	17	0.061	0.035–0.097	0.84	0.45–1.57
Lacrosse	317,041	23	0.073	0.046–0.109	1.00	
Field hockey	108,939	5	0.046	0.015–0.107	0.47	0.18–1.27
Football	162,650	11	0.068	0.034–0.121	1.68	0.78–3.63
Rugby	32,609	9	0.276	0.126–0.524	2.23	1.01–4.94
Volleyball	2237	1	0.447	0.011–2.491	2.57	0.34–19.38

From Beynnon et al. [4]

(RR) of female athletes suffering an ACL injury was 2.10 times greater than that of their male counterparts (Table 15.2). Previous studies had reported larger RR values (up to tenfold) in risk of injury between females and males; however, these studies did not consider the effect of gender independent of sport and level of play. Independently considering gender established a smaller but still statistically significant difference in relative risk.

After controlling for differences in gender and sport, collegiate athletes had an increased risk (RR = 2.38) of suffering an ACL injury compared with high school athletes. Further, when controlling for level of play and gender, the risk of suffering an ACL injury was highest in soccer (RR = 1.77) and rugby (RR = 2.23) compared with the other sports studied (basketball, lacrosse, football, field hockey, and volleyball). There were no statistical interactions between the effects of sport, level of play, and gender, thereby demonstrating the effects of these three risk factors were independent.

The estimated IR for individual female and male sports at the collegiate and high school levels were determined and compared to the IR data reported in the literature (Tables 15.3 and 15.4). This research included high school and collegiate athletes because they comprise a large proportion of ACL injuries that occur annually and focused on first-time noncontact ACL injuries because this is a common injury mechanism for these athletes. Investigation of first-time noncontact injury was important because an athlete's sport, gender, and level of play may have a different influence on ACL injuries produced by direct contact with the knee; however, it is unlikely that their effects are independent because the extent of contact varies between specific sports and level of competition, as well as between male and female sports.

15.3 Effect of Demographic Characteristics, Joint Laxity, Lower Extremity Alignment, and Strength on Risk of ACL Injury

Uhorchak et al. [22] conducted a prospective cohort study of noncontact ACL injuries in new military cadets enrolled at the United States Military Academy and who followed them for 4 years. A total of 24 ACL tears occurred. For female cadets, increased anterior-posterior knee laxity and increased body mass index (BMI) were associated with increased risk of ACL injury. The same model was applied to both sexes but was more predictive of risk for female cadets than for male cadets. For both female and male cadets, increased generalized joint laxity (evaluated with the Beighton test) and decreased femoral intercondylar notch width were associated with increased risk of suffering ACL injury.

A cohort study with a nested case-control analysis was conducted over a 4-year time interval

Table 15.3 First-time noncontact ACL injury rate estimates for male and female collegiate athletes based on Poisson regression results and corrected exposure days combined with comparison data from other studies

Sport	Estimated injury rate per 1000 athlete exposures				Comparison rates per 1000 athlete exposures	Study citation, descriptive information
	Original	95% CI	Corrected	95% CI		
Male						
Soccer	0.146	0.087–0.245	0.186	0.111–0.312	0.123*	Harmon et al., *overall for Divisions I, II, III
					0.13,* 0.120**	Arendt et al., *1989–1993, **1994–1998
					0.081*	Gwinn et al., *ACL tears requiring surgery only
					0.04,* 0.04,** 0.11$^{\#}$	Agel et al., *noncontact, **contact, $^{\#}$overall
					0.13,* 0.11,** 0.12$^{\#}$	Mihata et al., *1989–1994, **1994–2004, $^{\#}$1989–2004
					0.09	Hootman et al.
					0.12*	Prodromos et al., *weighted means for groups
Basketball	0.070	0.038–0.127	0.089	0.049–0.161	0.080*	Harmon et al., *overall for Divisions I, II, III
					0.07,* 0.101**	Arendt et al., *1989–1993, **1994–1998
					0.089*	Gwinn et al., *ACL tears requiring surgery only
					0.04,* 0.02,** 0.08$^{\#}$	Agel et al., *noncontact, **contact, $^{\#}$overall
					0.07,* 0.08,** 0.08$^{\#}$	Mihata et al., *1989–1994, **1994–2004, $^{\#}$1989–2004
					0.07	Hootman et al.
					0.08*	Prodromos et al., *weighted means for groups
Lacrosse	0.083	0.050–0.138	0.105	0.063–0.176	0.17	Mihata et al.
					0.12	Hootman et al.
					0.20	Mountcastle et al.
					0.17*	Prodromos et al., *weighted means for groups
Football	0.139	0.071–0.273	0.177	0.090–0.348	0.36,* 0.03,** 0.83,$^{\#}$ .05$^{\#\#}$	Dick et al., *noncontact/games, **noncontact/practices, $^{\#}$contact/games, $^{\#\#}$contact/practices
					0.18	Hootman et al.
					0.23	Mountcastle et al.
					0.806,* 0.08,** 0.142$^{\#}$	Dragoo et al., *games, **practices, $^{\#}$overall
Rugby	0.185	0.091–0.376	0.235	0.115–0.479	0.176*	Gwinn et al., *ACL tears requiring surgery only
					0.18*	Prodromos et al., *weighted means for groups

Female						
Soccer	0.307	0.195–0.482	0.391	0.249–0.614	0.321*	Harmon et al., *overall Divisions I, II, III
					0.31,* 0.330**	Arendt et al., *1989–1993, **1994–1998
					0.768*	Gwinn et al., *ACL tears requiring surgery only
					0.13,* 0.10,** 0.31$^{\#}$	Agel et al., *noncontact, **contact, $^{\#}$overall
					0.31,* 0.32,** 0.32$^{\#}$	Mihata et al., *1989–1994, **1994–2004, $^{\#}$1989–2004
					0.28	Hootman et al.
					0.32*	Prodromos et al., *weighted means for groups
					0.057,* 0.189,** 0.199,$^{\#}$ 0.340$^{\#\#}$ 0.057,* 0.113,** 0.170,$^{\#}$ 0.189$^{\#\#}$	Gilchrist et al., *noncontact w/conditioning, **noncontact control, $^{\#}$noncontact & contact w/conditioning, $^{\#\#}$noncontact & contact control *first-time noncontact w/conditioning, **first-time noncontact control, $^{\#}$first-time noncontact & contact w/ conditioning, $^{\#\#}$first-time noncontact & contact control
Basketball	0.146	0.084–0.253	0.186	0.108–0.322	0.297*	Harmon et al., *overall Divisions I, II, III
					0.29,* 0.289**	Arendt et al., *1989–1993, **1994–1998
					0.478*	Gwinn et al., *ACL tears requiring surgery only
					0.16,* 0.06,** 0.27$^{\#}$	Agel et al., *noncontact, **contact, $^{\#}$overall
					0.29,* 0.28,** 0.28$^{\#}$	Mihata et al., *1989–1994, **1994–2004, $^{\#}$1989–2004
					0.23	Hootman et al.
					0.39	Mountcastle et al.
					0.29*	Prodromos et al., *weighted means for groups
Lacrosse	0.174	0.106–0.285	0.221	0.135–0.363	0.18	Mihata et al.
					0.17	Hootman et al.
					0.18*	Prodromos et al., *weighted means for groups
Field hockey	0.082	0.033–0.204	0.105	0.042–0.260	0.07	Hootman et al.
Rugby	0.387	0.197–0.759	0.493	0.251–0.967	0.36	Levy et al.
					0.354*	Gwinn et al., *ACL tears requiring surgery only
					0.36*	Prodromos et al. *weighted means for groups
Volleyball	0.447	0.063–3.173	0.569	0.080–4.041	0.09	Hootman et al.

From Beynnon et al.

Table 15.4 First-time noncontact ACL injury rate estimates for male and female high school athletes based on Poisson regression results and corrected exposure days combined with comparison data from other studies

	Estimated injury rate per 1000 athlete exposures				Comparison rates per 1000 athlete exposures	
Sport	Original	95% CI	Corrected	95% CI		Study citation, descriptive information
Male						
Soccer	0.062	0.038–0.099	0.078	0.049–0.126	0.129,* 0.014,** 0.048$^{\#}$	Joseph et al., *competition, **practice, $^{\#}$overall
					0.050	Swenson et al.
Basketball	0.029	0.016–0.053	0.037	0.021–0.067	0.07	Messina et al.
					0.02*	Prodromos et al., *weighted means for groups
					0.055,* 0.009,** 0.023$^{\#}$	Joseph et al., *competition, **practice, $^{\#}$overall
					0.024	Swenson et al.
Lacrosse	0.035	0.020–0.594	0.044	0.026–0.076	0.079	Swenson et al.
Football	0.059	0.032–0.106	0.075	0.041–0.136	0.11*	Prodromos et al., *weighted means for groups
					0.467,* 0.041,** $^{\#}$0.111$^{\#}$	Joseph et al., *competition, **practice, $^{\#}$overall
					0.117	Swenson et al.
Female						
Soccer	0.129	0.087–0.192	0.164	0.111–0.244	0.09,* 0.49**	Mandelbaum et al., *noncontact/PEP trained, **noncontact control
					0.107**	Pfeiffer et al., *first-time noncontact/KLIP trained,**first-time noncontact control
					*: 0.08,** 0.45$^{\#}$	Prodromos et al., *weighted means for groups: **trained, $^{\#}$untrained
					0.352,* 0.024,** 0.122$^{\#}$	Joseph et al., *competition, **practice, $^{\#}$overall
					0.117	Swenson et al.
Basketball	0.061	0.036–0.105	0.078	0.046–0.133	0.03	Messina et al.
					0.476,* 0.111**	Pfeiffer et al., *first-time noncontact/KLIP trained, **first-time noncontact control
					*: 0.45,** 0.10$^{\#}$	Prodromos et al., *weighted means for groups: **trained, $^{\#}$untrained
					0.266,* 0.033,** 0.103$^{\#}$	Joseph et al., *competition, **practice, $^{\#}$overall
					0.107	Swenson et al.
Lacrosse	0.073	0.044–0.121	0.093	0.056–0.154	0.078	Swenson et al.
Field hockey	0.035	0.014–0.095	0.044	0.018–0.108	0.031	Swenson et al.

From Beynnon et al.

by Vacek et al. [23] that considered variables from five categories of risk factors (Table 15.5). This work revealed numerous risk factors are associated with increased risk of ACL injury and demonstrated that the risk factors are different for men and women. The study enrolled high school and collegiate athletes between the ages 14 and 23 who suffered a first-time noncontact ACL injury. Matched controls (age and gender) were selected from the same team as the injured player. One hundred and nine athletes with ACL injuries were included in the study with at least 2 controls per injured athletes (total of 227 control athletes). A majority of the potential risk factors were found to be different between genders, and consequently, the risk factors for male and female athletes were evaluated with separate multivariate risk models. For males, two measures of anatomic alignment and two measures of biomechanics were associated with increased risk of ACL injury. Presence of increased antero-posterior (AP) displacement of the tibia relative to the femur (or knee laxity, OR = 1.56), posterior knee stiffness (OR = 1.34), increased navicular drop (OR = 1.26), and decreased standing quadriceps angle (OR = 0.76) were associated with an increased risk of ACL injury. In women, two different multivariate models were developed. First, having a parent with a history of an ACL injury (OR = 3.84), increased anterior-posterior knee laxity (OR = 1.23), and increased trunk flexion strength (OR = 1.19) together were associated with an increased risk of noncontact ACL injury. For the second model, increased BMI (OR = 1.22) in combination with increased AP knee laxity (OR = 1.24) and having a parent who had suffered an ACL injury (OR = 3.8) were associated with increased risk of noncontact ACL injury. Although both male and female risk models included increased AP knee laxity as associated with increased risk of suffering ACL injury, they were otherwise dissimilar.

Table 15.5 Potential risk factors considered in a multivariate study of ACL injuries

Demographics	Strength	Lower extremity alignment	Joint laxity	Personality characteristics
Family history of ACL injury	Knee strength	Passive genu recurvatum	Knee	Temperament
Presence of chronic disease	– Flexion at 15°, 30°	Active genu recurvatum	– Anteroposterior knee laxity	– Novelty seeking
Race	– Extension at 15°, 30°	Hamstring extensibility	– Anterior knee stiffness	– Harm avoidance
Weight	Ankle strength	Tibiofemoral angle coronal plane	– knee stiffness	– Reward dependence
Height	– Flexion	Standing quadriceps angle	Ankle	– Persistence
Body mass index	– Extension	Navicular drop	– Talar tilt	Character
Hours spent training in sport/week	Hip strength	Pelvic angle	Generalized joint Laxity	– Self-directedness
Number year participating in sport	– Flexion	Tibial torsion	– Beighton test	– Cooperativeness
Use of braces	– Extension	Hip anteversion		– Self-transcendence
Use of medication	– Abduction	Length of femur		
Limb dominance	– Adduction	Length of tibia		
Prior leg surgery	– Internal			
Prior injury to knee	– External			
Prior injury to hip/thigh	Trunk strength			
Prior injury to ankle/foot	– Flexion			
Prior injury to lower leg	– Extension			

Study by Vacek et al. [34]

The findings from the studies conducted by Uhorchak et al. [22] and Vacek et al. [23] demonstrate that the characteristics that increase an athlete's risk of ACL injury are different for females and males. Indeed, in the work reported by Vacek et al. [23], when the male and female risk models were applied to the opposite sexes, they were no longer found to be significant predictors of ACL injury. This calls into question the approach of analyzing male and female risk of injury data together because it is possible that differences between sexes can minimize certain risk factors.

Another study of youth female soccer players investigated both intrinsic and extrinsic risk factors [1]. The intrinsic variables that were considered included BMI, onset of menarche, age, relative age effect (born in either the first or second half of the year), history of acute knee or ACL injury, family disposition of ACL injury (parents or siblings), and current knee complaints present at the beginning of the study. Extrinsic variables were exposure related and included the number of training sessions per week, the number of games per week, artificial turf exposure, match exposure ratio (match hours/total hours of play), and match play with other teams. Players with a sibling or parent with a history of an ACL injury were four times more likely to suffer an ACL injury themselves. Additionally, after analysis using Cox regression, a family history of an ACL history was established to be significant with a hazard ratio of 3.82. This value is similar to that reported by Vacek et al. [23].

A cross-sectional study of Israeli military recruits was conducted to determine the relationship between knee injury (ligament and meniscus injuries considered in combination) and gender, height, and BMI [24]. Using logistic regression, an individual's BMI was found to have a significant role in the likeliness of suffering knee ligament injury. In males and females, being underweight (BMI <5th percentile) was found to be protective against ligament and meniscus injury (OR = 0.488 in males and 0.549 in females). In contrast, an elevated BMI was found to increase one's risk of injury, more significantly in females than in males. Overweight males (OR = 1.176) had a significant increase in knee injuries, while overweight and obese females (OR = 1.406 and 1.519, respectively) had significant increased risk of concomitant ligament and meniscus injury. An increased height was also found to be associated with knee ligament injury. When comparing the tallest quintile of study participants with shorter individuals, taller individuals were more likely to suffer a ligamentous knee injury. This effect was more significant in females as there was no significant increased risk of injury in the shortest two quintiles. Additionally, if body height was evaluated as a continuous variable, a 1 cm increase in height was associated with a 3.6% odds ratio increase for females and a 3.9% increase for males.

15.4 Effect of Knee Geometry on Risk of ACL Injury

Relevant risk factors for ACL injury also include geometric characteristics of the knee. Males and females have different knee geometry, and, therefore, different elements of the knee could contribute to risk of injury [25]. A case-control study involving high school and collegiate athletes examined the knee geometry of individuals with a noncontact ACL injury and matched controls that were the same sex and age and participated on the same team using magnetic resonance imaging (MRI) [26]. The size of the ACL, the size of the femoral intercondylar notch, and the slope of the tibial plateau along with the geometry of the articular cartilage, menisci, and tibial spines were measured. These variables were chosen because they had all been shown to impact risk of ACL injury in previous studies that used univariate analysis. Using logistic regression, injury risk models were created for males and females. In males, the combined effects of smaller ACL volume and smaller wedge angle of the lateral posterior meniscal horn measured relative to the bone were most highly associated with risk of suffering ACL injury (OR = 1.43 and 1.23

Table 15.6 Best-fit multivariate risk model for male athletes[a]

Variable (unit change)	Odds ratio (95% CI)	*P* value
ACL_Vol ($100\ \text{mm}^3$)	1.43 (1.08–1.91)	0.013
$L_{at}T_{ib}$MBA (1 degree)	1.23 (1.01–1.50)	0.038

From Sturnick et al. [2]

[a] The model includes measures of anterior cruciate ligament (ACL) volume (ACL_Vol) and the lateral meniscus wedge angle measured relative to the bone ($L_{at}T_{ib}$MBA). Odds ratios and associated 95% confidence intervals (CI) describe the effect of a unit (100 mm^3 and 1 degree for ACL_Vol and $L_{at}T_{ib}$MBA, correspondingly) decrease from the mean for each variable on risk of suffering an ACL injury

per 0.1 cm^3 and 1° decreases, respectively; Table 15.6 and Fig. 15.1). Therefore, a male athlete who has decreased amounts of both ACL volume and wedge angle of the posterior meniscal horn relative to the mean values of his peers has approximately 1.76 times the risk of suffering an ACL injury (OR = 1.43 × 1.23 = 1.76). For females, a smaller femoral notch width at the anterior outlet combined with an increased posterior-inferior directed slope of the tibial lateral compartment articular cartilage surface produced the greatest risk of ACL injury (OR = 1.5 and 1.32 per mm decrease and degree increase, respectively; Table 15.7 and Fig. 15.2). Thus, a

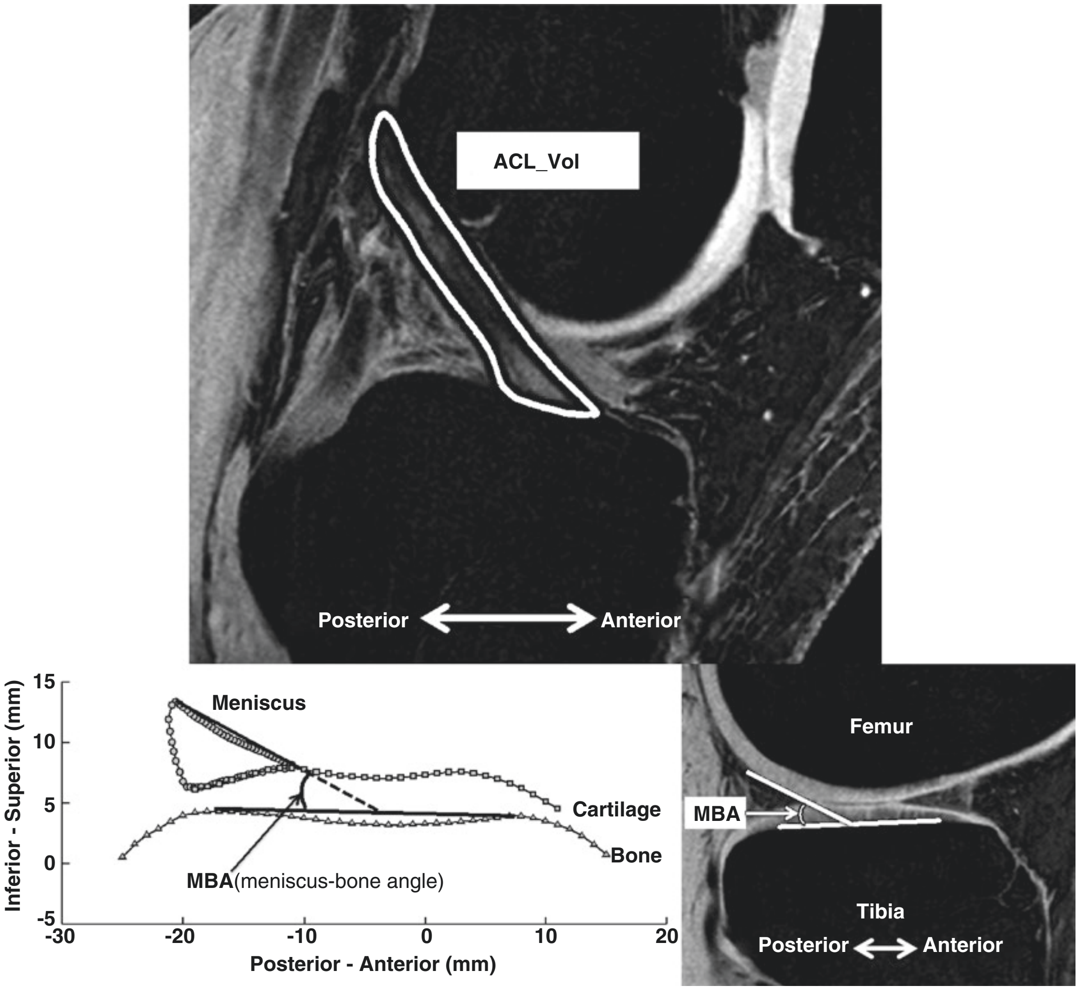

Fig. 15.1 Measurements of knee geometry that best predict risk of noncontact ACL injury in males, including volume of the ACL (ACL_Vol) and the meniscus bone angle of the tibial plateau in the lateral compartment (MBA). Decreased ACL volume and decreased meniscus bone angle increased risk of ACL injury. From Sturnick et al. [26]

Table 15.7 Best-fit multivariate risk model for female athletes[a]

Variable (unit change)	Odds ratio (95% CI)	*P* value
$L_{at}T_{ib}MCS$ (1 degree)	1.324 (1.135–1.546)	0.0004
NW_O (1 mm)	1.500 (1.135–1.980)	0.004

From Sturnick et al. [2]

[a]The model includes measures of lateral compartment middle region articular cartilage slope ($L_{at}T_{ib}MCS$) and the femoral intercondylar notch width at the anterior outlet of the ACL (NW_O). Odds ratios and associated 95% confidence intervals (CI) describe the effects of a unit (1 degree) increase from the mean for $L_{at}T_{ib}MCS$ and a unit (1 mm) decrease from the mean for NW_O on risk of suffering an ACL injury

female athlete who differs in both variables by the above amounts from the mean values for her peers has double the risk of sustaining an ACL injury (1.5 × 1.32 = 1.98). Using these models, the authors were able to demonstrate the fact that when combined, risk factors were able to identify athletes at increased risk of ACL injury.

A case-control study by Beynnon et al. also confirmed the significance of an increased posterior-inferior directed slope of the subchondral bone portion of the middle of the lateral tibial plateau as a risk factor for noncontact ACL injury, especially in female athletes [27]. MRIs of high school and collegiate athletes that suffered an ACL tear and their matched control were obtained, and subchondral bone geometry was analyzed. The posterior-inferior directed slopes of the medial and lateral tibial plateaus, the coronal tibial slope, and the medial tibial plateau depth were measured bilaterally for each athlete. When adjusting for the other variables, an increased posterior-inferior

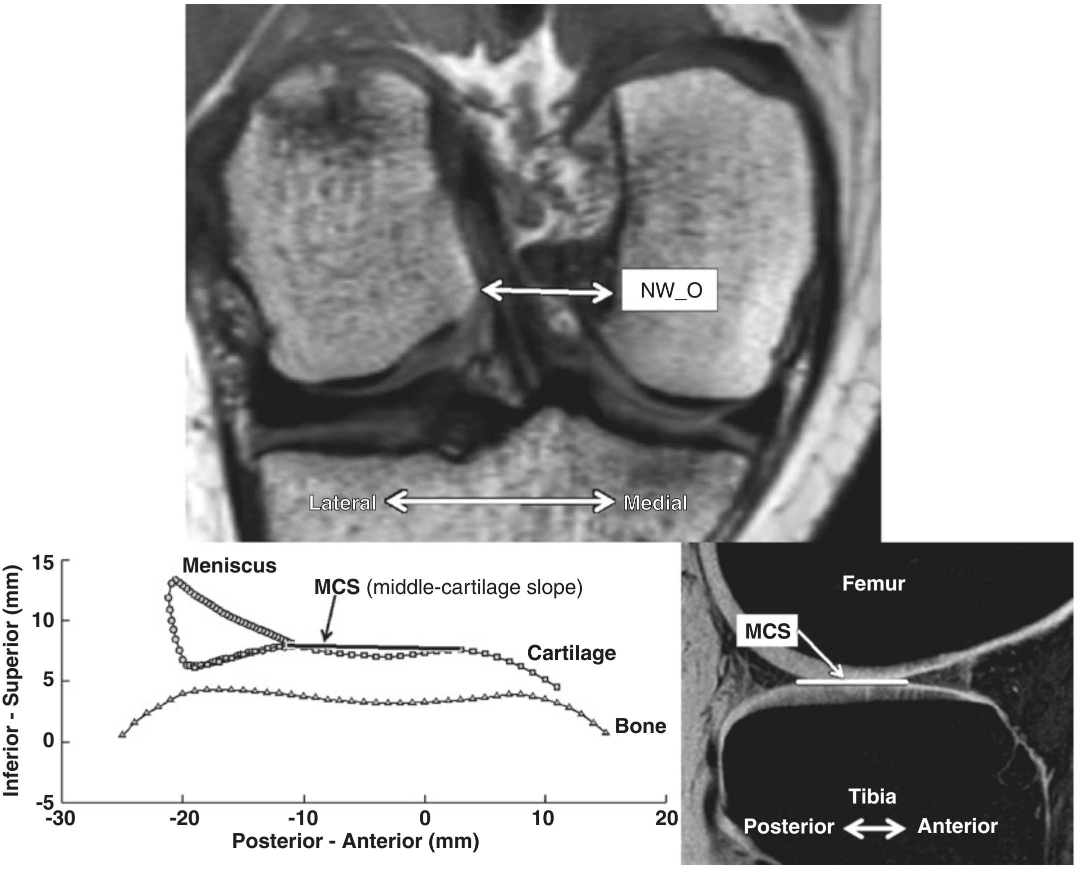

Fig. 15.2 Measurements of knee geometry that best predict risk of noncontact ACL injury in females, including the femoral intercondylar notch width at the anterior outlet (NW_O) of the notch and the slope of the articular cartilage surface in the middle region of the lateral tibial plateau (MCS). Decreased notch width and increased slope in these locations increased risk of noncontact ACL injury. From Sturnick et al. [26]

directed lateral tibial plateau slope was significantly associated with an increased risk of ACL injury. When evaluating risk in female athletes, each 1° increase of lateral tibial slope was associated with a 31.9% increased risk of noncontact ACL injury (OR = 1.319); however, no association was seen when considering males as a group.

The significance of increased posterior-inferior directed tibial plateau slope and decreased femoral intercondylar notch width in relation to increased risk of ACL injury appears to be supported by additional reports in the literature [28–31]. While these studies used MRI for three-dimensional knee geometry measurements, they did not evaluate risk factors for males and females separately.

An additional cross-sectional study investigating the significance of the posterior-inferior directed tibial plateau slope found that an increased slope of the lateral plateau was significantly associated with increased risk of ACL injury [31]. MRIs of individuals who had undergone ACL reconstruction and a control group of individuals with patellofemoral syndrome were evaluated for the medial and lateral tibial slopes. Demographic data including age, sex, and race were also collected to further characterize individuals at risk of suffering ACL injury. Race was recorded as either white, black, Asian, other, or unknown. Laterality of the injury (right vs left) was documented as well. Univariate regressions and multivariate risk models were created using this knee geometry and demographic data. Younger age and an increased lateral posterior-inferior directed tibial slope were associated with an increased risk of ACL injury (OR = 0.94 and OR = 1.12, respectively). When comparing the univariate regressions of these variables to the multivariable regression for the same variables, the multivariate regression was found to be a better fit model, and, therefore, considering the risk factors together was found to be a more complete predictor of ACL injury. Additionally, while gender appeared to be a significant risk factor (OR = 1.88), its inclusion in the multivariate regression did not improve the predictive value of the statistical model.

Conclusion

Overall, the multivariate analysis literature demonstrates the importance of considering variables in combination to best predict the risk of first-time, noncontact ACL injury. Increased risk of injury was seen in numerous studies when variables were considered together. Additionally, females were shown to be at greater risk of injury when compared to males independent of sport and level of play. Increased anterior-posterior knee laxity, decreased femoral notch width, increased lateral posterior-inferior directed tibial plateau slope, increased BMI, and family history of ACL injury were found to act in combination to predict injury in females in more than one study [22–24, 26, 27, 31, 32]. Combined factors were also noted to increase a male's risk of ACL injury. These include generalized joint laxity, increased anterior-posterior knee laxity, and a smaller ACL volume [22, 23, 26]. The impact of increased BMI appears to be less in males in comparison to females, and likewise, the importance of increased posterior-inferior directed slope of the lateral tibial plateau in males is not as well established as it is in females as contradictory results exist [24, 27, 31]. These results demonstrate the multifactorial nature of ACL injury risk factors and how they differ between males and females. AP knee laxity, knee geometry, and demographics all have an influence on risk of suffering ACL trauma, as do level of play and choice of sport for athletes [4]. With this information it may be possible to begin targeting athletes at greatest risk of noncontact ACL injury with ACL injury prevention programs.

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16

Testing for Neuromuscular Problems and Athletic Performance

Sue Barber-Westin and Frank R. Noyes

Abstract

This chapter reviews cost-effective tests to determine neuromuscular deficiencies and indicators of athletic performance. The identification of athletes who may have an increased risk of sustaining a noncontact ACL rupture is highly important in the continued development of knee injury prevention programs. No single test has been found to be highly predictive of at-risk athletes. Common body mechanics and injury circumstances have been noted during or just following ACL ruptures, such as 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. Cost-effective tests are recommended that depict these abnormal mechanics during activities such as landing from a jump, cutting, or sidestepping. Field tests are described that are commonly used to estimate maximal oxygen uptake and measure speed, agility, vertical jump height, dynamic balance, and strength before and after ACL intervention training. Other testing options that require sophisticated equipment (such as magnetic resonance imaging) are presented for anatomical indices (intercondylar notch, tibial slope) that appear to play a role in ACL injury risk. The potential importance of performance scores on neurocognitive (concussion) tests is discussed.

16.1 Introduction

The identification of athletes who may have an increased risk of sustaining a noncontact anterior cruciate ligament (ACL) rupture is of paramount importance in the continued development of knee injury prevention programs. The ability to detect certain individuals who may be predisposed to this injury entails understanding all of the risk factors discussed in Sect. 16.2. While some potential factors (such as anatomical or field conditions) may not be alterable, research has shown that high-risk neuromuscular characteristics can be successfully changed which we believe reduces the incidence of noncontact ACL injuries. In this chapter, various factors to consider and testing options to use based on available funds and facilities are discussed. It is important to note that no single test has been found to be highly predictive of at-risk athletes; multivariate analyses are required, and our understanding of the hierarchy of all of the possible risk factors remains inconclusive at present [1]. It is important to also

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acknowledge that some cost-effective, reliable tests which may correlate with biomechanical indicators of ACL injury risk in the laboratory have not proven to be predictive of actual future ACL injury [2, 3]. One example is the Landing Error Scoring System, which was shown to be not able to predict noncontact ACL injury in a cohort of 5047 high school and collegiate athletes [4].

Common body mechanics and injury circumstances have been noted in both men and women during or just following ACL ruptures. Video footage obtained during noncontact 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 [5–7]. Therefore, tests are recommended that depict these abnormal mechanics during activities such as landing from a jump, cutting, or sidestepping. Although the majority of research conducted over the past two decades on neuromuscular indices has used expensive force plate, multi-camera motion analysis systems, there are cost-effective test methods available.

Critical Points

- Identification of athletes with increased risk of noncontact ACL rupture important for continued development of knee injury prevention programs
- No single test predictors for high-risk athlete; multivariate analyses required
- Common body mechanics and injury circumstances noted in men and women during or just following ACL ruptures
- Tests recommended that show abnormal mechanics on landing from a jump, cutting, or sidestepping

16.2 Neuromuscular and Balance

16.2.1 Video Drop-Jump Screening Test

A drop-jump video screening test may be used to measure overall lower limb alignment in the coronal plane [8–10]. 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. 16.1).

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 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) takeoff, 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. 16.1 The drop-jump land sequences from a 16-year-old female athlete before and 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%)

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. 16.2). 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 [8]. Test-retest trials produced high intraclass correlation coefficients (ICC) for the hip separation distance (pre-land, 0.96; land, 0.94; takeoff, 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 interrater reliability between athletic trainers, physical therapists, surgeons, and coaches in determining knee separation distance (K coefficient = 0.92) [9].

If desired, a second camera may be implemented to assess knee and hip flexion angles in the sagittal plane [11]. 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 [12].

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

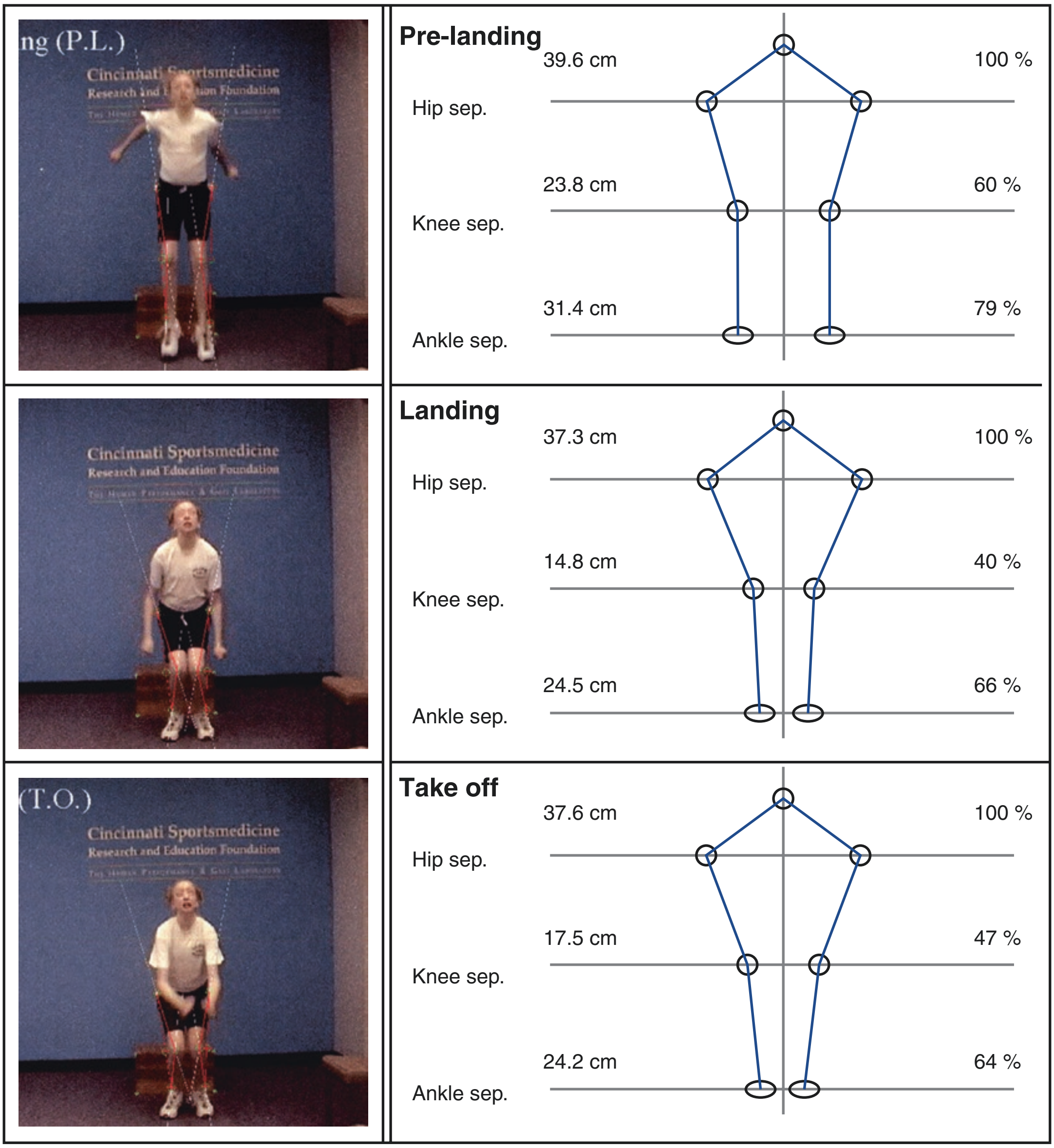


Fig. 16.2 Photographs of the three phases of the drop-jump test. The cm of distance between the hips, knees, and ankles is calculated along with normalized knee and ankle separation distances (according to the hip separation distance). Shown is the test result of a 14-year-old female (From Noyes FR, Barber-Westin SD, Fleckenstein C et al. (2005). The drop-jump screening test: Difference in lower limb control by gender and effect of neuromuscular training in female athletes. Am J Sports Med 33 (2):197–207)

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 [13]. 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.

16.2.2 Single-Leg Functional Hop Tests

Single-leg functional hop tests are one of the most commonly used measures of lower extremity power and dynamic balance [14–18]. 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 [19]. 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 [20].

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. 16.3a). 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. 16.3b). In some instances, players will not be able to hold the landing at all and may even fall toward the ground (Fig. 16.3c). 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.

16.2.2.1 Single-Leg Hop [19, 20]

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 seconds (s) (Fig. 16.4a). 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 [21, 22]. Significant correlations have been reported between limb symmetry scores for this test and knee extensor peak torque tested isokinetically [20, 23–25].

16.2.2.2 Single-Leg Triple Hops [19]

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. 16.4b). 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. Right-left leg limb symmetry 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 on this test and isokinetic peak torque for the quadriceps and hamstrings at 60°/s and 180°/s [26]. The ICC of this test is excellent (>0.87 [21, 27]).

16.2.2.3 Single-Leg Triple Crossover Hop [19]

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. 16.4c). 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 right-left leg limb symmetry index calculated as described above. This test has excellent reliability, with ICC > 0.85 [21, 27]. Significant correlations have been reported between limb symmetry scores for this test and knee extensor peak torque tested isokinetically [24].

Fig. 16.3 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 SD, Noyes FR (2017): Decreasing the risk of anterior cruciate ligament injuries in female athletes. In *Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes*, 2nd Edition, Elsevier, Philadelphia, pp. 373–404)

16.2.2.4 Timed Single-Leg Hop [19, 20]

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 right-left leg limb symmetry index is calculated using the average time for each leg. This test has excellent reliability, with ICCs >0.90

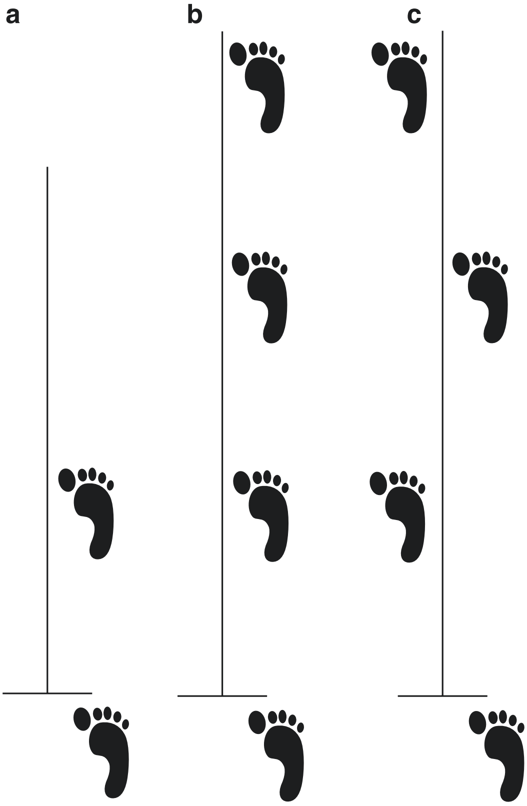


Fig. 16.4 Single-leg hop tests. (**a**) Single hop. (**b**) Triple hop. (**c**) Triple crossover hop

[21, 27, 28]. Significant correlations have been reported between limb symmetry scores for this test and knee extensor peak torque tested isokinetically [24].

16.2.3 Single-Leg Squat Test

The single-leg squat test is a useful and reliable clinical tool that requires control of the body over one planted leg which may be used to detect poor hip strength and trunk control (see Chap. 13) [29–32]. Studies have shown that, during this test, females have more ankle dorsiflexion, ankle pronation, hip adduction, hip flexion, hip external rotation, and less trunk lateral flexion than men [33]. Women also assume a greater overall valgus lower extremity alignment than men [33–35]. Correlations have been noted between performance on this test in regard to control of frontal plane knee motion and hip muscle strength [31, 36, 37].

The single-leg squat is conducted by asking the athlete to stand on one 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. 16.5). If the foot is touched on the floor or if contact occurs with the other (non-weight-bearing) leg, the trial is repeated. The test result may be classified according to five categories that are rated as good, fair, or poor (Table 16.1) [31]. To receive a good rating, the athlete must achieve all of the requirements for four of the five criteria. The athlete's performance is considered poor if they do not meet all of the requirements for at least one criterion. 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 reliabilities have been reported in several studies [29–32].

16.2.4 Star Excursion Balance Test

The Star Excursion Balance Test (SEBT) has been used extensively to measure dynamic postural control in uninjured athletes [38–47], athletes who completed neuromuscular retraining [40, 48–50], patients with chronic ankle instability [51–54], patients with low back pain [55–57], and individuals with an ACL injury [58–61]. 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 [62]. This test has adequate reliability between sessions (ICC, 0.84–0.93 [43, 63, 64]) and under inter-tester (ICC, 0.81–0.93 [65, 66]) and intra-tester (ICC, 0.81–0.96 [40, 63, 64, 66] conditions.

The test should be conducted on a firm hard surface, such as concrete or a gymnastics floor,

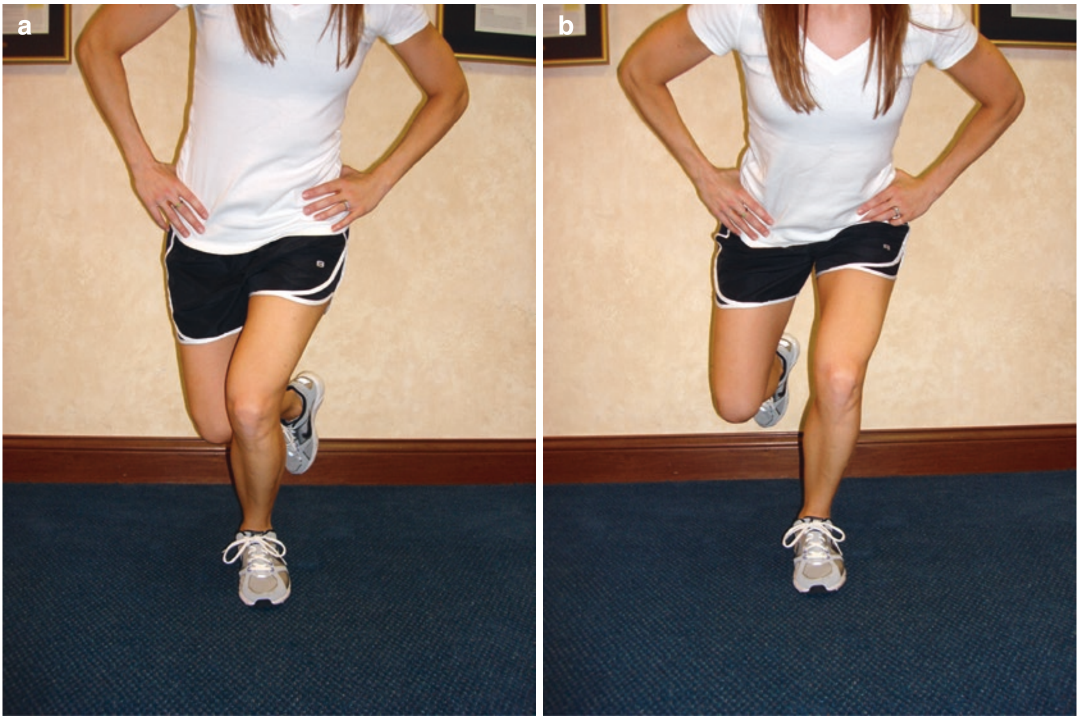


Fig. 16.5 Single-leg squat test. (**a**) Poor hip and knee control. (**b**) Good hip, trunk, and knee control. (From Barber-Westin SD, Noyes FR (2017): Risk Factors for anterior cruciate ligament injuries in the female athlete. In *Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes*, 2nd Edition, Elsevier, Philadelphia, pp. 344–372)

Table 16.1 Clinical rating criteria for the single-leg squat test [31]

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 the knee remains over center of the foot

s seconds

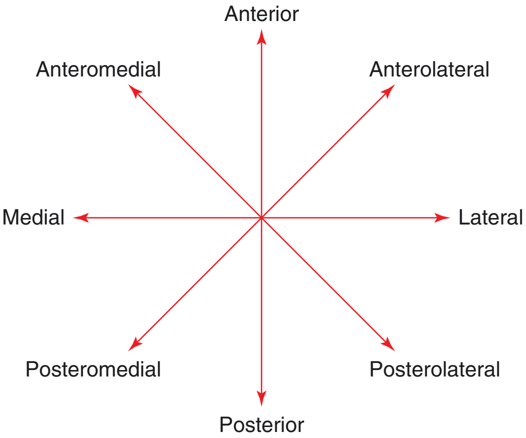


Fig. 16.6 Star Excursion Balance Test. Directions are shown for a right limb stance

and the subject should be barefooted. A grid is made on the floor consisting of eight 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. 16.6). The athlete places their hands on their hips and places the most distal aspect of their great toe on the center of the grid. While maintaining a single-leg stance on one 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 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 three 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 three 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 lengths are used to normalize reach distances by dividing the distance reached by the leg length and then multiplying by 100 (Table 16.2) [70]. 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 [43, 69].

Critical Points

- Video drop-jump screening: single coronal plane, <60% normalized knee separation distance abnormal lower limb valgus alignment, good test-retest and within-test reliability
- Single-leg hop tests: normal limb symmetry, ≥ 85%; correlates with isokinetic knee extensor peak torque; good reliability
- Single-leg squat test: detects poor hip strength, trunk control, acceptable interrater and intra-rater reliability
- Star Excursion Balance Test: measures dynamic postural control and acceptable inter-session, inter-tester, and intra-tester reliability

16.3 Athletic Performance

16.3.1 Field Test Considerations

Many testing procedures are available to determine changes in athletic performance following neuromuscular training. This chapter provides an overview of field tests commonly used to estimate maximal oxygen uptake and measure speed, agility, vertical jump height, dynamic balance, and strength before and after ACL intervention training. Also, recommendations are made for sports-specific field tests for basketball, soccer, volleyball, and tennis based on our experience and an extensive review of the medical literature. Other resources are available for further test recommendations and procedures [71–74]. Whether a correlation exists between the results of these tests and an increased risk for a noncontact ACL injury is unknown and requires future investigation. The tests chosen have reported acceptable reliability in measuring the specific functional tasks, as will be discussed. They are practical to administer and require limited equipment and personnel resources.

Table 16.2 Star excursion balance test normalized reach distances[a]

Study	Population	Anterior	Anteromedial	Posterior	Posteromedial	Posterolateral	Medial	Lateral
Steffen et al. [46]	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. [50]	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. [67]	40 female collegiate athletes							
	Right side	69 ± 6			107 ± 10	106 ± 10		
	Left side	68 ± 6			112 ± 10	103 ± 10		
McLeod et al. [48]	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. [68]	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. [69]	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. [43]	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

Before testing, the athlete completes the dynamic warm-up component of Sportsmetrics training (see Chap. 17). Each test is thoroughly explained, and the athlete is allowed several practice trials so that he/she is familiar with the procedures. Education of the athlete regarding the importance of testing and need for maximal effort is crucial to obtain valid results. 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 [75]. 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 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 [74]. Longer-lasting tests may require 8 min between repetitions and test trials.

16.3.2 Estimated Maximal Oxygen Uptake: Multistage Fitness Test

Aerobic fitness is a critical component for athletic performance and injury prevention [76]. 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. One of the most common is the 20-m multistage fitness test (MSFT) [77].

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. 16.7). 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 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 16.3). The athletes’ VO_2max is estimated using the equation described by Ramsbottom et al. [78]:

$$VO_2\max = \left(5.857 \times \text{speed on the last stage}\right) - 19.458$$

The results may be analyzed according to gender- and age-matched percentile groups published by the American College of Sports Medicine [79] (Table 16.4) or compared to those published according to sport and gender

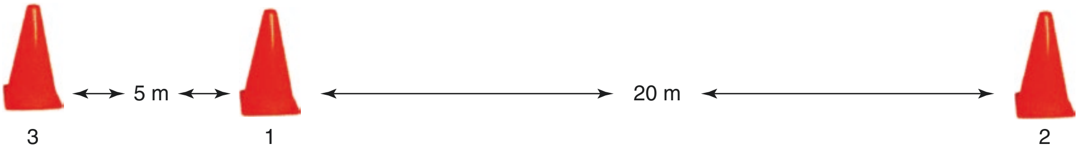


Fig. 16.7 Course used for the 20-m multistage fitness test (cones #1 and #2 only) and the 20-m Yo-Yo intermittent test (cones #1, #2, and #3)

Table 16.3 Predicted maximum oxygen uptake values for multistage fitness test[a]

Level	No. of shuttles	Predicted VO_2 max	Level	No. of shuttles	Predicted VO_2 max
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	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	14	10	63.2
6	8	35.7	14	13	64
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
8	4	41.1	16	4	68.5
8	6	41.8	16	6	69
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	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			
12	10	56.5			
12	12	57.1			

[a] From the Department of Physical Education and Sports Science, Loughborough University, 1987

Table 16.4 Interpretation of multistage fitness test results according to the American College of Sports Medicine[a]

Females: estimated VO_2max							
Gender	Age, year	Very poor	Poor	Fair	Good	Excellent	Superior
Females	13–19	<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
Females	20–29	<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
Females	30–39	<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
Females	40–49	<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
Females	50–59	<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
Females	60+	<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

[a] From the Physical Fitness Specialist Certification Manual, the Cooper Institute for Aerobics Research, Dallas, X, revised 1997

Printed in Advance Fitness Assessment and Exercise Prescription, 3rd Edition, Vivian H. Heyward, 1998, p. 48

(Table 16.5). The MSFT has been used to determine cardiovascular fitness levels in basketball [80, 81], soccer [82–89], volleyball [90–94, 101], rugby [95–98], and tennis [99, 100]. Test-retest reliability of the MSFT has been reported by others to be excellent, with ICCs ≥0.90 [77, 102–104]. The validity of this test in regard to estimating cardiorespiratory fitness has also been calculated to be acceptable [105].

16.3.3 Intermittent Recovery: Yo-Yo Test Level 1 and Level 2

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 [106–108]. The Yo-Yo intermittent recovery test was developed to measure an athlete's ability to repeatedly perform intense exercise [109]. It is similar in manner 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. These tests have been studied extensively in athletes participating in recreational team sports, badminton, basketball, soccer, rugby, team handball, volleyball, and field hockey [109–126]. 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) [86, 109, 110, 114, 127–130].

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. 16.7. The athlete begins with their toes behind the designated starting cone (cone #1 in Fig. 16.7). 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 progres-

Table 16.5 Sample results of estimated VO_2max (mL kg^{-1} min^{-1}) from multistage fitness testing according to sport and gender

Study	Sport, gender	Age, years	VO_2max
Noyes et al. [80]	Basketball, high school females	14–17	
	Before neuromuscular training		34.6 ± 4.5
	After neuromuscular training		39.5 ± 5.7
Ben Abdelkrim et al. [81]	Basketball, elite, male	18.2 ± 0.5	53.18 ± 2.66
Noyes et al. [82]	Soccer, high school females	12–18	
	Before neuromuscular training		37.9 ± 4.5
	After neuromuscular training		40.1 ± 4.7
Meckel et al. [83]	Soccer, elite adolescent, male	16–18	54.1 ± 3.1
Nassis et al. [84]	Soccer, semipro, male	22.8 ± 2.5	50.7 ± 3.1
Caldwell et al. [85]	Soccer, semipro, male	24 ± 4.4	58.0 ± 1.9
Hill-Haas et al. [86]	Soccer, elite youth, SSG train, male	14.6 ± 0.9	60.2 ± 4.6
	Soccer, elite youth, GTG train, male		59.3 ± 4.5
Aziz et al. [87]	Soccer, elite, male	17.7 ± 0.4	57.8 ± 5.0
Gabbett et al. [88]	Soccer, elite, trained, female	18.3 ± 2.8	48.8 ± 3.6
	Soccer, elite, control, female		52.1 ± 5.1
Guy et al. [89]	Soccer, recreational league, male		
	Experimental group	26.6 ± 8.2	44.0 ± 6.7
	Placebo-trained group	23.9 ± 6.7	42.9 ± 8.7
	Control group	21.3 ± 4.9	46.3 ± 6.2
Noyes et al. [90]	Volleyball, high school females	14.5 ± 1.0	
	Before neuromuscular training		39.4 ± 4.8
	After neuromuscular training		41.4 ± 4.0
Gabbett et al. [91]	Volleyball, IT, male and female	15.6 ± 0.1	45.7 ± 2.0
	Volleyball, SBC, male and female		43.8 ± 2.0
Gabbett et al. [92]	Volleyball, national, male		50.6 ± 1.4
	Volleyball, national, female		41.2 ± 0.9
	Volleyball, state, male		49.8 ± 1.1
	Volleyball, state, female		39.3 ± 0.7
	Volleyball, novice, male		41.2 ± 1.2
	Volleyball, novice, female		37.0 ± 0.8
Gabbett et al. [93]	Volleyball, junior, pre-train	15.5 ± 0.2	40.8 ± 1.1
	Volleyball, junior, post-train		43.2 ± 1.1
	Gender unknown		
Duncan et al. [94]	Volleyball, elite, setters, male		46.9 ± 4.9
	Volleyball, elite, hitters, male		51.1 ± 3.7
	Volleyball, elite, centers, male		50.4 ± 3.7
	Volleyball, elite, opposites, male		48.3 ± 6.7
Gabbett et al. [95]	Rugby, semipro, first grade, male		51.9 ± 3.3
	Rugby, semipro, second grade, male		51.1 ± 4.5
Gabbett et al. [96]	Rugby, junior, male	16–17	46.3
	Rugby, senior, male	23–27	44.9
Gabbett et al. [97]	Rugby, elite, forwards, female		32.2 ± 4.4
	Rugby, elite, backs, female		35.3 ± 3.4
	Rugby, elite, hit-up forwards, female		31.2 ± 3.3
	Rugby, elite, adjustables, female		36.2 ± 4.6
	Rugby, elite, outside backs, female		34.5 ± 2.2

Table 16.5 (continued)

Study	Sport, gender	Age, years	VO_2max
Till et al. [98]	Rugby, league, Under 13 s		47.9 ± 5.4
	Rugby, league, Under 14 s		50.1 ± 4.7
	Rugby, league, Under 15 s		51.3 ± 4.6
Fargeas-Gluck and Leger [99]	Elite junior tennis players	12.9 ± 0.3	54.2 ± 5.9
Brechbuhl et al. [100]	Elite junior tennis players	16.8 ± 0.9	56.5 ± 5.6

SSG small-sided training program, *GTG* generic training program, *IT* instructional training, *SBC* skill-based conditioning game

Table 16.6 Yo-Yo intermittent recovery test level 1 protocol [131]

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 16.7 Yo-Yo intermittent recovery test level 2 protocol [131]

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

sively 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 16.6 and 16.7). 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 [109]. Instead, it is recommended that the total distance recorded be used to evaluate an athlete's ability to repeatedly perform intermittent exercise (Table 16.8).

16.3.4 Speed Tests

16.3.4.1 Sprint Tests: 10, 20, and 36.6 m

Sprint tests are used to determine acceleration, speed, and quickness. These tests may be accomplished with a measuring tape or a marked track, cone markers, and a stopwatch or timing gates. The athlete performs a single maximum sprint, starting from a stationary position with 1 ft in front of the other. Encouragement is provided throughout the run. Two tests are performed, with the best time recorded to the nearest 100th of a second. The reliability of sprint tests is excellent, with ICCs > 0.90 using either a handheld stopwatch or timing gates [132–135]. The results may be compared with published data according to sport and gender (Table 16.9).

Table 16.8 Sample results of the Yo-Yo intermittent recovery test according to sport and gender

Study	Gender (no.), age	Sport, level	Yo-Yo IR1 test, m	Yo-Yo IR2 test, m
Serpiello et al. [123]	Male (7) and female (3), 22.3 ± 4.1 years	Recreational athletes		
		Pre-train	1305 ± 709	NA
		Post repeated-sprint train	1400 ± 715	NA
Sirotic and Coutts [124]	Female (16), 20.9 ± 1.8 years	Team sport athletes, regional-level teams	958 ± 368	NA
Bangsbo et al. [109]	Female, 21 years	Badminton, high-level (N = unknown)	1200	NA
	Female, 17 years	Badminton, high-level (N = unknown)	1080	NA
Castagna et al. [111]	Male (22), 16.8 ± 2.0 years	Basketball, club	1678 ± 397	NA
Bangsbo et al. [109]	Male (12), age unknown	Basketball, junior players of professional club	NA	590
Klusemann et al. [116]	Male (17), 14 ± 1 years and female (21), 15 ± 1 years	Basketball, adolescent players		
		Supervised trained group (13) Pre-post	822 ± 640/978 ± 528	NA
		Video trained group (13) Pre-post	797 ± 385/834 ± 414	NA
		Control group (13) Pre-post	916 ± 370/862 ± 363	NA
Lockie et al. [117]	Female, 20.2 ± 1.2 years	Soccer, collegiate	1666 ± 473	533 ± 164
Bradley et al. [110]	Female (199), elite 23 ± 2 years	Soccer, European national elite teams (92)	NA	1774 ± 532
	Elite youth 19 ± 1 years	Elite youth teams U-20 (42)	NA	1490 ± 447
	Recreational 22 ± 3 years	Recreational teams (46)	NA	1261 ± 449
	Sub-elite 23 ± 4 years	Sub-elite teams (19)	NA	994 ± 373
Bangsbo et al. [109]	Male (256), age unknown	Soccer, top-elite ($N = 54$)	NA	1260
		Moderate-elite ($N = 130$)	NA	1050
		Sub-elite ($N = 72$)	NA	840
Bangsbo et al. [109]	Female (181), age unknown	Soccer, top-elite ($N = 44$)	1600	NA
		Moderate-elite ($N = 74$)	1360	NA
		Sub-elite ($N = 63$)	1160	NA
Rampinini et al. [122]	Male (25), 25 ± 5 years	Soccer, Professional ($N = 13$)	2231 ± 294	958 ± 99
		Amateur ($N = 12$)	1827 ± 292	613 ± 125

Fanchini et al. [114]	Male (20), 24 ± 6 years	Soccer, semi-pro		
		Pre-season	1695 ± 243	NA
		Post-season	2385 ± 412	NA
Nicks et al. [120]	Male (20) and female (7), 19.8 ± 0.9 years	Soccer, collegiate		
		Pre-train	1250 ± 351	NA
		Post-respiratory muscle training	1466 ± 486	NA
Flatt and Esco [113]	Female (12), 22 ± 2.3 years	Soccer, collegiate	1250 ± 247	NA
Dupont et al. [112]	Male (14), 23.2 ± 3.5 years	Soccer, amateur adult	2034 ± 367	NA
Makhlouf et al. [118]	Male (57), 13.7 ± 0.5 years	Soccer, young elite		NA
		Endurance-strength trained (14) pre/post	931 ± 177/1663 ± 219	NA
		Strength-endurance trained (15) pre/post	1034 ± 308/1642 ± 339	NA
		Strength-endurance alternated trained (14) pre/post	974 ± 273/1505 ± 306	NA
		Control (14) pre/post	945 ± 260/1234 ± 330	NA
Moss et al. [119]	Female (120), Non-elite 15.7 ± 1.3 years; Elite 15.8 ± 1.3 years; Top-elite 17.1 ± 1.1 years	Handball		
		Non-elite	906 ± 324	NA
		Elite	935 ± 394	NA
		Top-elite	1663 ± 327	NA
Souhail et al. [125]	Male (18), 14.3 ± 0.5 years	Handball, team	1831 ± 373	NA
Jones et al. [115]	Female (27), 23.5 ± 4.1 years	Rugby, elite		
		Backs	728 ± 154	NA
		Forwards	610 ± 292	NA
Purkhus et al. [121]	Female (25), 19 ± 5 years	Volleyball, elite		
		High-intensity trained pre-post	NA	191 ± 43/215 ± 32
		Control pre-post	NA	193 ± 62/204 ± 63
Vescovi [126]	Female (44), U 21 and U17 teams	Field hockey, national team players		
		U21 team (20)	1480 ± 332	NA
		U17 team (24)	1068 ± 220	NA

Yo-Yo IR1 Yo-Yo intermittent recovery level 1, *Yo-Yo IR2* Yo-Yo intermittent recovery level 2, *NA* not available

Table 16.9 Sample results of sprint tests according to sport and gender

Study	Population details	9.1-m (10-y), s	10-m (10.9-y), s	18.2-m (20-y), s	20-m (21.9-y), s	27.4-m (30-y), s	30-m (32.8-y), s	36.6-m (40-y), s
Noyes[80]	Basketball, females aged 14–17 years							
	Pre-train	NA	NA	3.54 ± 0.3	NA	NA	NA	NA
	Post-train	NA	NA	3.53 ± 0.4	NA	NA	NA	NA
Delextrat [136]	Basketball, female elite, aged 24.3 ± 4.1 years	NA	NA	NA	3.78	NA	NA	NA
Ben Abdelkrim [81]	Basketball, male elite, aged 18.2 ± 0.5 years	NA	1.98 ± 0.17	NA	3.23 ± 0.18	NA	4.31 ± 0.18	NA
Delextrat [136]	Basketball, female elite, age NA	NA	NA	NA	3.50 ± 0.23	NA	NA	NA
Delextrat [137]	Basketball, U16 national teams							
	Females	NA	NA	NA	3.84 ± 0.32	NA	NA	NA
	Males	NA	NA	NA	3.60 ± 0.18	NA	NA	NA
Klusemann [116]	Basketball, males aged 14 ± 1 years and females aged 15 ± 1 years							
	Supervised train	NA	NA	NA	3.56 ± 0.21	NA	NA	NA
	Online video train	NA	NA	NA	3.52 ± 0.20	NA	NA	NA
	Control	NA	NA	NA	3.50 ± 0.22	NA	NA	NA
Hoffman [138]	Lacrosse, females aged 19.2 ± 1.0 years							
	Elite, starters	NA	NA	NA	NA	NA	NA	5.4 ± 0.16
	Elite, nonstarters	NA	NA	NA	NA	NA	NA	5.5 ± 0.16

Lockie [117]	Soccer, female collegiate	NA	1.98 ± 0.05	NA	NA	NA	4.73 ± 0.13	NA
Noyes [82]	Soccer, females aged 14–17 years							
	Pre-train	NA	NA	NA	NA	NA	NA	6.11 ± 0.43
	Post-train	NA	NA	NA	NA	NA	NA	5.99 ± 0.38
de Hoyo [139]	Soccer, males, U19 national team							
	Full-back squat post-train	NA	1.68 ± 0.08	NA	2.94 ± 0.10	NA	4.07 ± 0.11	NA
	Resisted sprint post-train	NA	1.71 ± 0.06	NA	2.88 ± 0.08	NA	4.19 ± 0.13	NA
	Plyometric post-train	NA	1.72 ± 0.08	NA	2.98 ± 0.12	NA	4.13 ± 0.17	NA
Hammami [140]	Soccer, male, aged 15.4–16.1 years							
	Experimental group post-train	NA	1.75 ± 0.11	NA	3.08 ± 0.16	NA	4.35 ± 0.21	NA
	Control group	NA	1.90 ± 0.16	NA	3.27 ± 0.24	NA	4.57 ± 0.35	NA
Mirkov [141]	Soccer, pro, male, 20.4 ± 1.8	NA	1.90 ± 0.08	NA	2.52 ± 0.10	NA	NA	NA
Vescovi [142]	Soccer, females aged 15.1 ± 1.6 years	1.96 ± 0.10	NA	3.33 ± 0.15	NA	4.63 ± 0.21	NA	5.94 ± 0.28
	Soccer, females aged 19.9 ± 0.9 years	2.00 ± 0.11	NA	3.38 ± 0.17	NA	4.69 ± 0.23	NA	5.99 ± 0.29
	Lacrosse, females aged 19.7 ± 1.1 years	1.99 ± 0.09	NA	3.37 ± 0.14	NA	4.66 ± 0.20	NA	5.97 ± 0.27

(continued)

Table 16.9 (continued)

Study	Population details	9.1-m (10-y), s	10-m (10.9-y), s	18.2-m (20-y), s	20-m (21.9-y), s	27.4-m (30-y), s	30-m (32.8-y), s	36.6-m (40-y), s
Gabbett [92]	Volleyball, mean age 16.5 ± 0.1 years							
	National, male	NA	1.80 ± 0.02	NA	NA	NA	NA	NA
	National, female	NA	1.90 ± 0.01	NA	NA	NA	NA	NA
	State, male	NA	1.76 ± 0.03	NA	NA	NA	NA	NA
	State, female	NA	1.95 ± 0.02	NA	NA	NA	NA	NA
	Novice, male	NA	1.81 ± 0.02	NA	NA	NA	NA	NA
	Novice, female	NA	2.03 ± 0.03	NA	NA	NA	NA	NA
Trajkovic [143]	Volleyball, males, aged 22.3 ± 3.7 years							
	Pre-train	NA	1.92 ± 0.02	NA	NA	NA	NA	NA
	Post-train	NA	1.90 ± 0.01	NA	NA	NA	NA	NA
Darrall-Jones [144]	Rugby, males aged 17.7 ± 0.6 years							
	Union	NA	1.04 ± 0.04	NA	3.12 ± 0.10	NA	4.36 ± 0.16	NA
	League	NA	1.01 ± 0.03	NA	3.10 ± 0.06	NA	4.30 ± 0.10	NA
Dello Iacono [145]	Handball, males, elite, aged 24.8 ± 4.4 years							
	Small-sided game post-trained	NA	2.00 ± 0.06	NA	2.70 ± 0.10	NA	NA	NA
	Repeated shuffle sprint post-trained	NA	1.97 ± 0.06	NA	2.68 ± 0.09	NA	NA	NA

Ulbricht [146]	Tennis, national juniors							
	Male U12	NA	2.00 ± 0.08	NA	3.52 ± 0.19	NA	NA	NA
	Male U14	NA	1.95 ± 0.08	NA	3.45 ± 0.13	NA	NA	NA
	Male U16	NA	1.85 ± 0.07	NA	3.22 ± 0.12	NA	NA	NA
	Female U12	NA	2.02 ± 0.06	NA	3.60 ± 0.11	NA	NA	NA
	Female U14	NA	1.99 ± 0.08	NA	3.50 ± 0.14	NA	NA	NA
	Female U16	NA	1.93 ± 0.09	NA	3.38 ± 0.15	NA	NA	NA
Munivrana [147]	Tennis, national junior players							
	Males aged 16.9 ± 1.7 years	NA	NA	NA	3.4 ± 0.2	NA	NA	NA
	Females aged 16.7 ± 1.7 years	NA	NA	NA	3.7 ± 0.2	NA	NA	NA
Jones [148]	Collegiate female athletes							
	Pre-train	NA	NA	NA	NA	4.83 ± 0.14	NA	NA
	Post-train	NA	NA	NA	NA	4.78 ± 0.14	NA	NA
Sekulic [149]	Collegiate athletes							
	Males	NA	1.95 ± 0.12	NA	3.35 ± 0.24	NA	NA	NA
	Females	NA	2.17 ± 0.18	NA	3.75 ± 0.26	NA	NA	NA

OS open skills warm-up, *CS* closed skills warm-up, *NA* not available

16.3.4.2 Suicide Run

Suicide runs are a common measure of speed for many different types of sports and are usually conducted on either a basketball, volleyball [133, 134], or tennis court [150]. On the basketball court, the athlete begins from a standing position behind the baseline and runs at maximal speed to four different lines: the near free throw line, the half-court line, the far free throw line, and the far baseline. After they arrive at each line, they sprint back to the original baseline. On the tennis court, 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 (Fig. 16.8). 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 100ths of a second. While suicide runs are frequently used for both testing and training, few data have been reported in the medical literature on the expected standards for various sports for either gender.

16.3.5 Agility Tests

16.3.5.1 T-Test

Since its initial description in the literature in 1990 [151], the T-test has become one of the most widely used measures of agility [81, 93, 133, 134, 152, 153]. The athlete sprints from a standing point in a straight line to a cone placed 9 m away (Fig. 16.9). 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 backward 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 100ths of a second. This test has excellent reliability, with ICCs ≥0.90 [154, 155]. The results may be compared with published data according to sport and gender (Table 16.10).

16.3.5.2 Pro-agility Test

Also known as the 5-10-5 test, the pro-agility test is a common field test for soccer players (Fig. 16.10) [148, 159]. If done on a marked football field, the athlete begins on the 5-yard line, sprints 4.5 m to the goal line, and touches the line with their hand. The athlete then changes direction and sprints to the 10-yard line (9 m away). They touch that line, reverse direction, and return to the 5-yard line starting point (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 100ths of a second. The results may be compared with published data according to sport and gender (Table 16.10).

16.3.5.3 Baseline Forehand/Backhand Tests [150, 162]

The baseline forehand and backhand tests are useful speed and agility tests for tennis players [162]. 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. 16.11). The athlete begins on the center of the baseline and upon command, runs to the 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.

16.3.5.4 Service Box Test [150, 162]

The service box test is another appropriate speed and agility test for tennis players [162]. 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

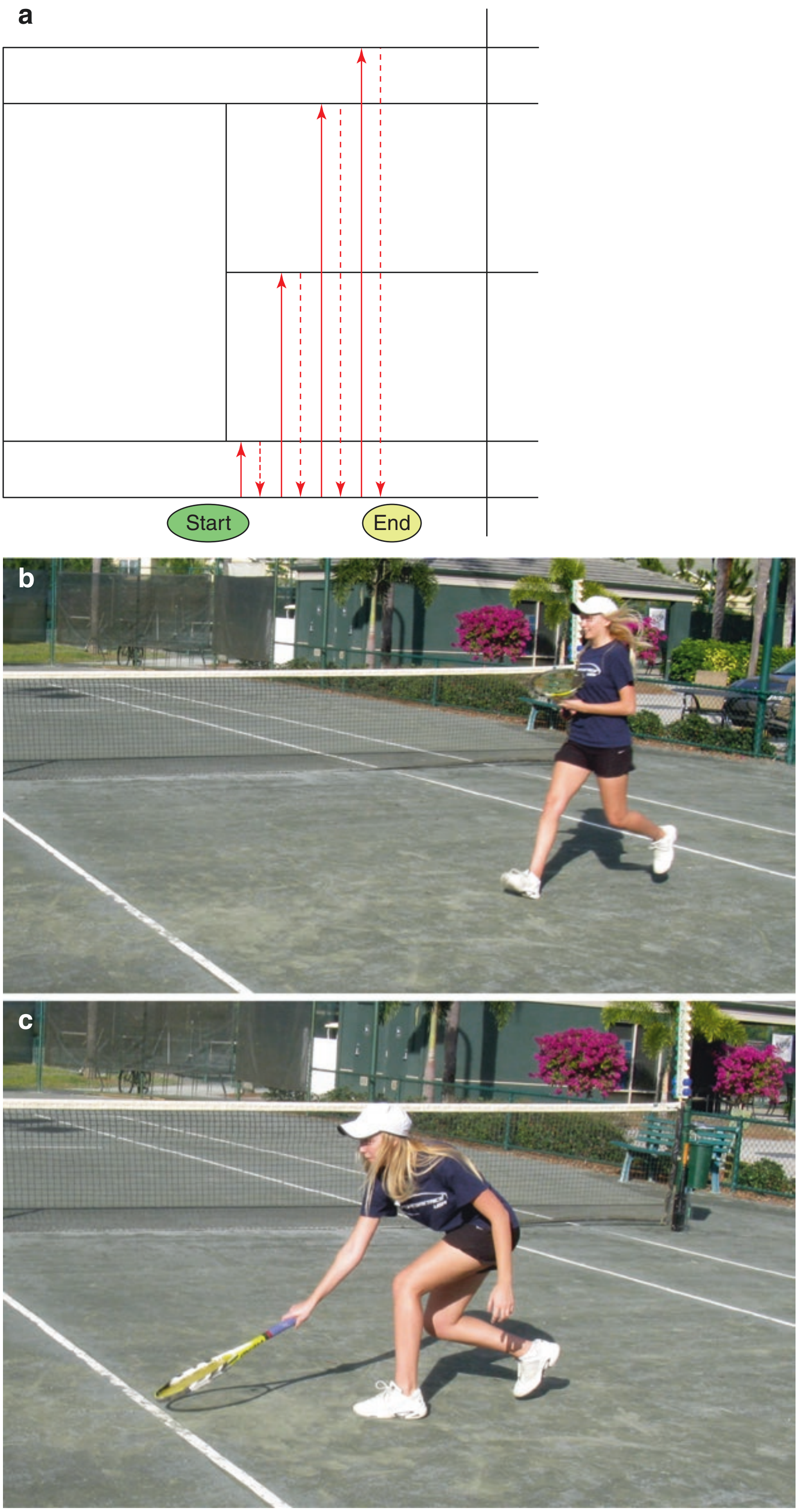
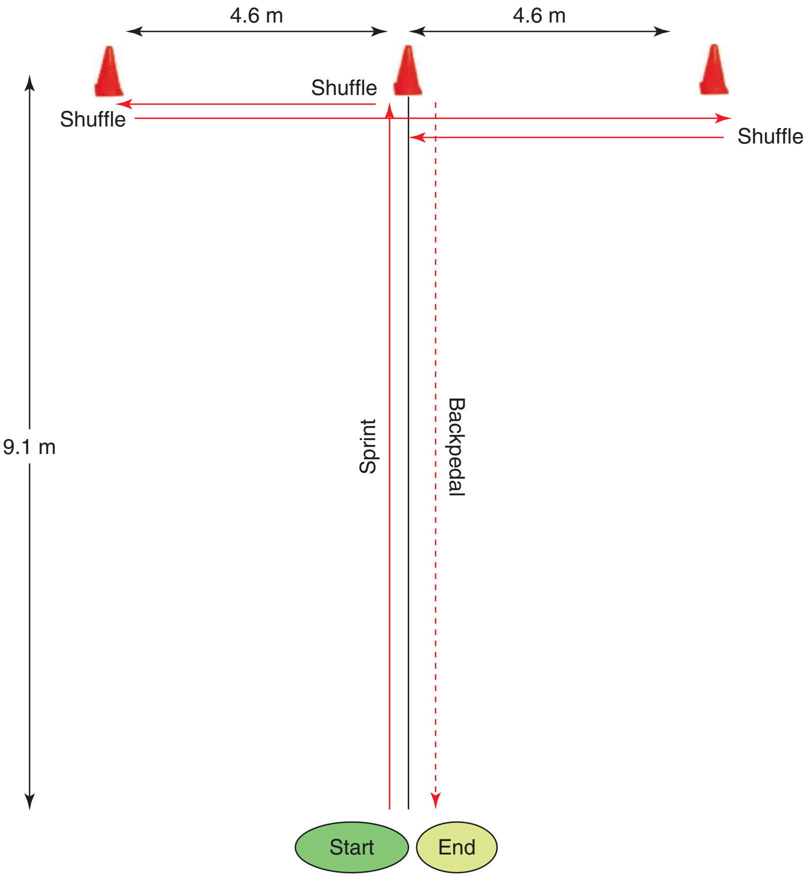


Fig. 16.8 The one-court suicide is run in a straight line; the figure depicts the eight segments individually for illustrative purposes only. Solid lines indicate forward sprinting; dotted lines indicate backpedaling

Fig. 16.9 T-test. The test requires the athlete to follow the directions shown with the red arrows in consecutive order from start to finish



the singles sideline with their racquet, going back and forth as many times as possible within 30 s (Fig. 16.12). Each time the player touches a line counts as one 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 [150].

16.3.6 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. 16.13). Reliability for the assessment of vertical jump height using the Vertec is excellent, with ICCs >0.90 [163, 164]. The results may be compared with published data according to sport and gender (Table 16.11).

16.3.7 Abdominal Strength and Endurance

16.3.7.1 Sit-Up Tests [174, 175]

Sit-up tests may be used to assess muscular strength and endurance. With the athlete lying supine with the knees bent and feet flat on the floor

Table 16.10 Sample results of agility tests according to sport and gender

Study	Sport, gender, age	Pro-agility, s	*T*-test, s
Jones [148]	Collegiate female athletes		
	Pre-train	5.39 ± 0.24	NA
	Post-train	5.37 ± 0.25	NA
Ben Abdelkrim [81]	Basketball, elite, male, aged 18.2 ± 0.5 years	NA	11.56 ± 0.46
Spiteri [156]	Basketball, professional, female, age 24.2 ± 2.5 years	NA	11.75 ± 1.15
Delextrat [134]	Basketball, elite, female, age NA	NA	10.45 ± 0.51
Delextrat [133]	Basketball, elite, male, age NA Basketball, average-level, male, age NA	NA	9.49 ± 0.56
Hoffman [138]	Lacrosse, elite, female, aged 19.2 ± 1.0 years		
	Starters	4.92 ± 0.22	10.5 ± 0.6
	Nonstarters	4.94 ± 0.13	10.5 ± 0.2
Lockie [17]	Soccer, collegiate, female	5.08 ± 0.16	NA
McFarland [157]	Soccer, collegiate		
	Females	5.36 ± 0.18	11.92 ± 0.56
	Males	4.64 ± 0.14	10.22 ± 0.41
Noyes [82]	Soccer, high school, female, age 15 ± 1 years	NA	12.05 ± 0.87
Vescovi [142]	Soccer, high school, female, aged 15.1 ± 1.6 years	4.91 ± 0.22	NA
	Soccer, collegiate, female, aged 19.9 ± 0.9 years	4.88 ± 0.20	NA
	Lacrosse, collegiate, female, aged 19.9 ± 0.9 years	4.99 ± 0.24	NA
Sporis [158]	Soccer, elite, male, aged 19.1 ± 0.6 years	NA	8.12 ± 0.27
Magal [159]	Soccer, elite, male aged 20.0 ± 0.9 years		
	Preseason	4.96 ± 0.19	NA
	Postseason	4.80 ± 0.33	NA
Gabbett [92]	Volleyball, mean age 16.5 ± 0.1 years		
	National, male	NA	9.90 ± 0.17
	National, female	NA	10.33 ± 0.13
	State, male	NA	9.76 ± 0.15
	State, female	NA	10.55 ± 0.14
	Novice, male	NA	10.47 ± 0.18
	Novice, female	NA	11.23 ± 0.16
Stewart [160]	Healthy collegiate physical education students		
	Male	4.88 ± 0.26	10.59 ± 0.61
	Female	5.35 ± 0.28	12.14 ± 0.62
Bishop [161]	Rugby, elite, male U17	4.67 ± 0.16	NA

NA not available

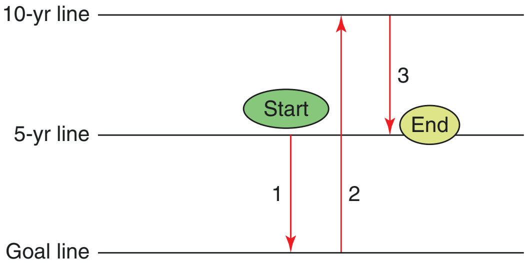


Fig. 16.10 The pro-agility test consists of three forward sprints as shown. Course shown is an American football field

(held in place by a partner) and arms folded across the chest, sit-ups are performed by rising up so that the elbows touch the knees and then lying back down 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) [242] and chronic pain populations of 0.77 (ICC, test–retest) and 1.0 (ICC, interrater) [176].

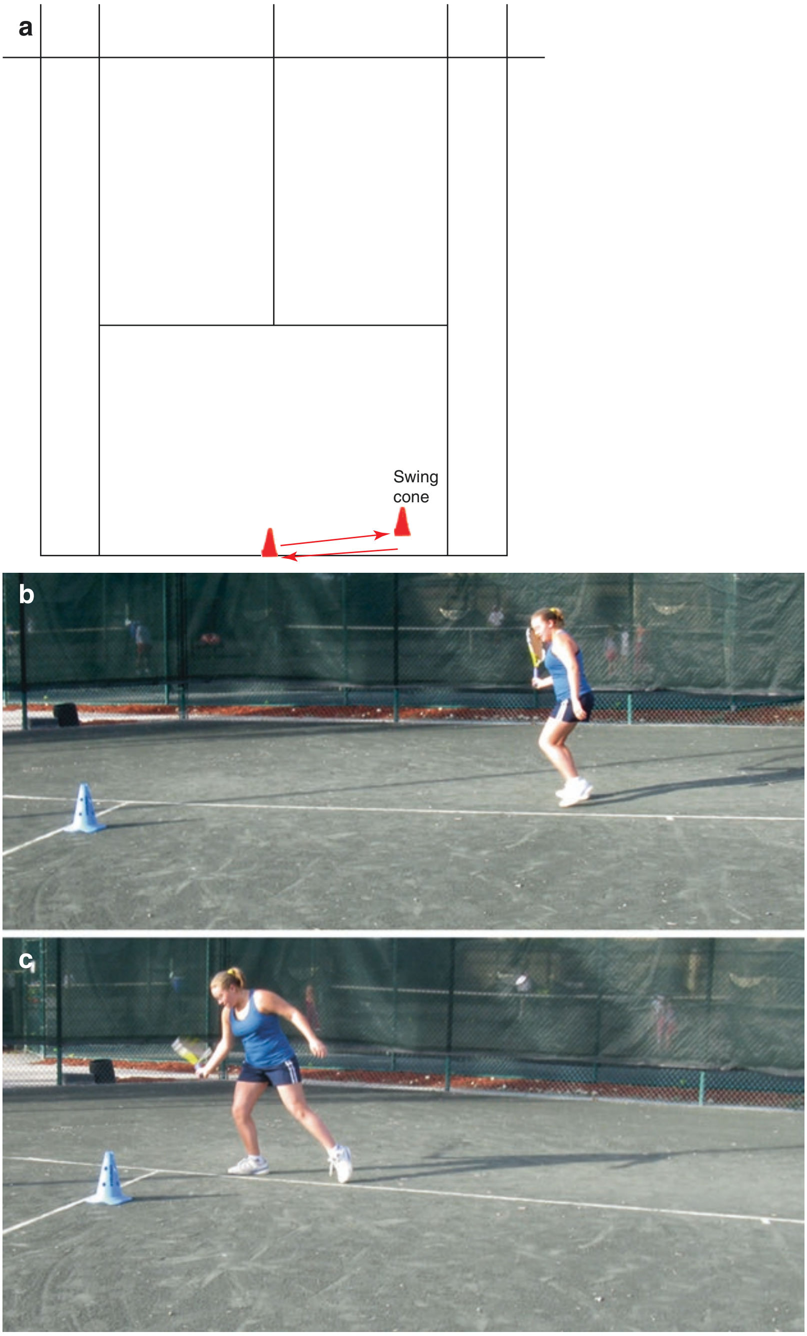


Fig. 16.11 Baseline speed and agility forehand and backhand test. (From Barber-Westin SD et al.: A 6-week neuromuscular training program for competitive junior tennis players. J Strength Condit Res 24: 2372–2382, 2010)

16.3.7.2 Abdominal Endurance Test [150]

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.

Fig. 16.12 Service box speed and agility test. (From Barber-Westin SD et al.: A 6-week neuromuscular training program for competitive junior tennis players. J Strength Condit Res 24: 2372–2382, 2010)

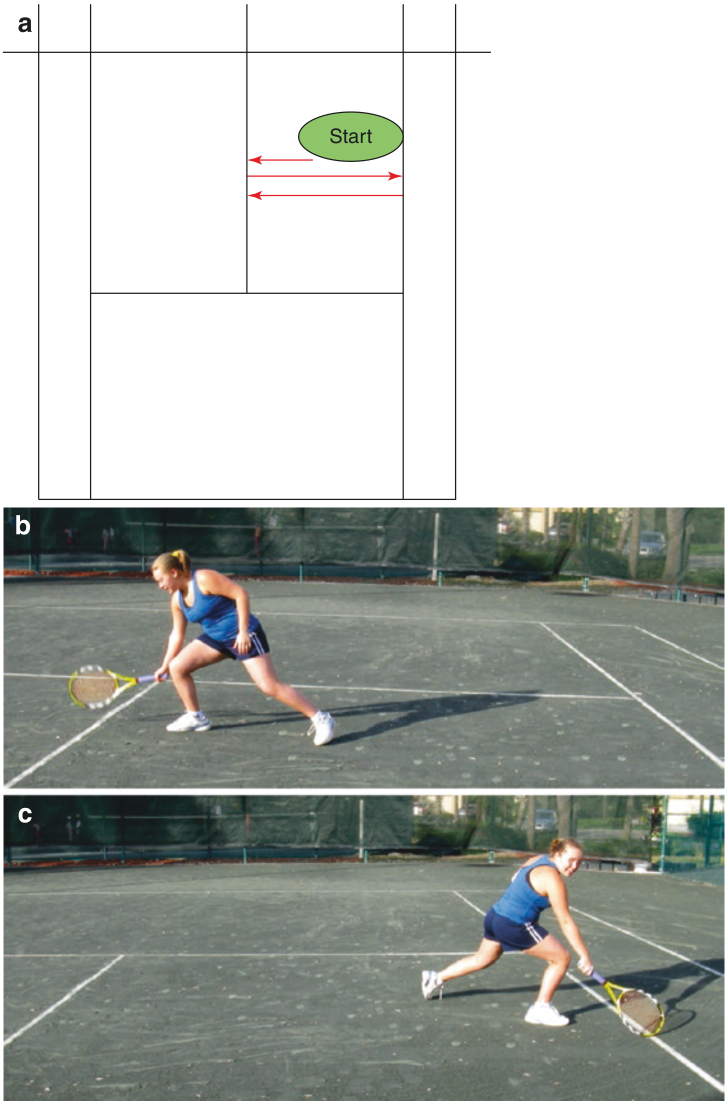


Fig. 16.13 Vertical jump test using Vertec

Table 16.11 Sample results of countermovement vertical jump height according to sport and gender

Study	Sport, gender, age	Measurement method	Distance, cm
Laffaye [165]	Collegiate and professional athletes	Force plate	
	Males		57.9 ± 7.0
	Females		42.6 ± 6.3
Jones [148]	Collegiate athletes, female	Vertec	
	Pre-train		48.5 ± 6.3
	Post-train		49.8 ± 5.9
Vescovi [142]	Female athletes	Electronic timing mat	39.6 ± 4.7
	High school soccer, aged 15.1 ± 1.6 years		
	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 [138]	Lacrosse, elite, female, aged 19.2 ± 1.0 years	Vertec	
	Starters		38.4 ± 5.6
	Nonstarters		36.6 ± 6.1
Enemark-Miller [166]	Lacrosse, elite, female, aged 20.0 ± 1.4 years	Vertec	44.0 ± 6.2
Gabbett [135]	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 [167]	Basketball, high school females	Vertec	
	Frontal-plane plyometric pre-trained		48.26 ± 5.39
	Sagittal-plane plyometric pre-trained		47.72 ± 7.07
Roden [168]	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 [169]	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 [170]	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 [90]	Volleyball, high school females, aged 15 ± 1 years	Vertec	40.1 ± 7.1
McFarland [157]	Soccer, collegiate	Electronic jump mat	
	Females		41.85 ± 4.98
	Males		58.47 ± 6.53
Harper [171]	Soccer, collegiate, males	NA	32.9 ± 6.1
de Hoyo [139]	Soccer, elite male, aged 18 ± 1 years	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 [172]	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 [82]	Soccer, high school females aged 15 ± 1 years	Vertec training system	32.9 ± 6.7
Steffen [173]	Soccer, high school females aged 16–18 years	Force platform	27.9 ± 3.2
Gabbett [97]	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

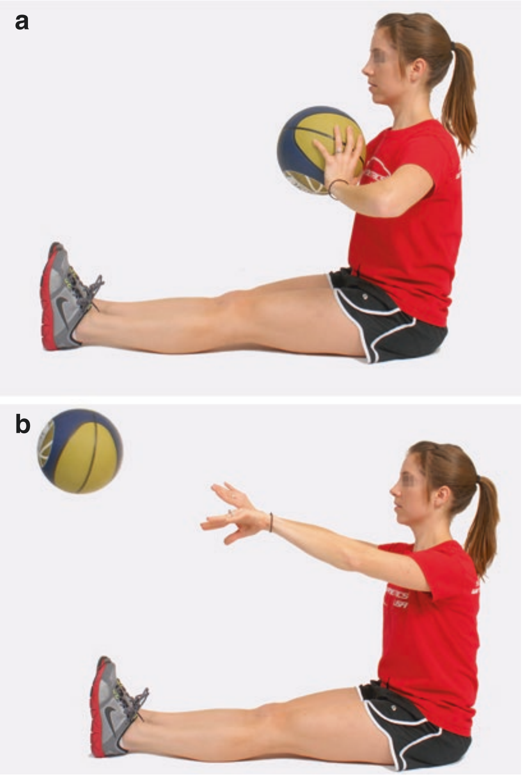


Fig. 16.14 Sitting chest pass

16.3.8 Upper Body Strength and Power

16.3.8.1 Sitting Chest Pass

The sitting chest pass is a convenient way to assess upper body strength [177–180]. 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. 16.14). The player is asked to push a basketball in the horizontal direction as far as possible using a two-handed chest pass. Three trials are completed, with the farthest toss recorded. Excellent reliability (ICC 0.98) and positive correlations (*R* range, 0.59–0.80) have been reported between this test and isokinetic shoulder and elbow strength [178].

16.3.8.2 Medicine Ball Toss: Chest Pass, Forehand Toss, Backhand Toss, and Overhead Toss

The medicine ball toss is another commonly used test to measure upper body strength and power [181, 182]. The athlete stands one step behind a 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 [182] (Fig. 16.15a–d). Three trials are completed, with the farthest toss recorded. Significant correlations were reported between this test and isometric maximum trunk rotation torque and one-repetition maximum bench press for male athletes [183]. In elite male and female tennis players, significant correlations were reported between isokinetic trunk rotation peak torque and single-repetition work and both the forehand and backhand medicine ball toss [184].

16.3.9 Sports-Specific Field Test Recommendations

Table 16.12 shows the sports-specific field tests recommended for athletes participating in basketball, soccer, volleyball, and tennis. The tests were selected based on an extensive search of the medical literature that included scientific investigations, meta-analyses, and reviews [21, 22, 73, 81, 83, 93, 132–135, 141, 142, 148, 152–154, 159, 183–197]. The tests estimate maximal oxygen uptake and provide objective measurements of speed, agility, anaerobic power, dynamic balance and power, and strength. Appropriate rest periods are emphasized to allow a return of resting heart rate, hydration, and preparation for the next task.

For all sports, a one-repetition max (1 RM) bench press and leg press are recommended if weight room equipment is available, along with an experienced test administrator and a sufficient amount of time to safely conduct these tests [73, 198]. For these tests, the athlete should warm up by performing 5–10 repetitions of the exercise at 40–60% of their estimated 1 RM. After 1 min of rest, the athlete performs 3–5 repetitions of the exercise at 60–80% of their estimated 1 RM. Then, with a conservative increase in weight, the athlete should attempt a 1 RM lift. If successful, a rest period of 3–5 min is allowed.

Fig. 16.15 Medicine ball toss for tennis players. (**a**, **b**) Backhand. (**c**, **d**) Overhead

Table 16.12 Field test recommendations according to sport

Sport	Recommended tests	Optional tests
Basketball	Countermovement vertical jump Single-leg triple crossover hop T-test 20-m sprint Abdominal endurance or sit-up test Chest pass (medicine ball or basketball) Yo-Yo test	Star Excursion Balance Test Speed shot shooting test Controlled dribble test 1-Rep max bench press, leg press Multistage fitness test
Soccer	Countermovement vertical jump Single-leg triple crossover hop Pro-agility test 10-m sprint 20-m sprint Abdominal endurance or sit-up test Overhead toss with soccer ball Yo-Yo test	Star Excursion Balance Test 1-Rep max bench press, leg press Multistage fitness test Loughborough soccer dribble test Haaland soccer dribble test Johnson wall volley test
Volleyball	Countermovement vertical jump Spike (approach) vertical jump Single-leg triple crossover hop T-test 20-m sprint Abdominal endurance or sit-up test Overhead medicine ball toss Yo-Yo test	Star Excursion Balance Test 1-Rep max bench press, leg press Multistage fitness test
Tennis	Single-leg triple crossover hop Baseline forehand, backhand tests Service line tests 1-Court suicide 2-Court suicide Abdominal endurance or sit-up test Medicine ball toss: forehand, backhand, overhead Yo-Yo test	Star Excursion Balance Test 1-Rep max bench press, leg press Multistage fitness test

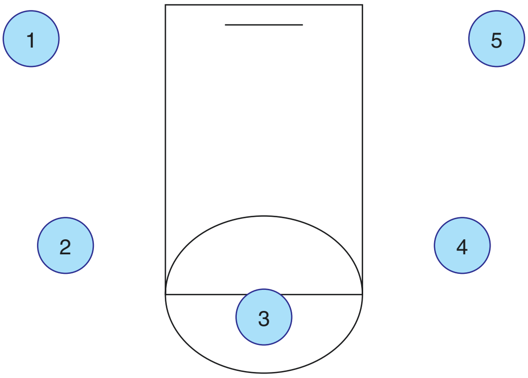


Fig. 16.16 Speed shot shooting test. Each spot numbered 1–5 is 4.5 m from the center of the backboard

Then, the weight is increased, and the same procedure is followed until the athlete cannot complete the lift. The 1 RM value is the maximum weight lifted. Excellent reliability has been reported for the leg press, with ICC of 0.99 [73].

For basketball players, a speed-shot shooting test may be conducted as described by the American Alliance for Health and Physical Education, Recreation, and Dance [199]. The gym floor is marked with five spots at a distance of 4.5 m from the center of the backboard (Fig. 16.16). First, a 6-min warm-up is completed which consists of lay-ups 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 his/her own ball and dribbles to a subsequent spot. Four lay-up shots are allowed, but no two lay-ups in succession. Each basket made equals two 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 [199]. The results may be placed into percentile groups according to gender and age (Table 16.13).

A second basketball test involves a controlled dribble [199]. An obstacle course is marked using six cones in the free throw lane of the court (Fig. 16.17). 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 score used for analysis. The results may be placed into percentile groups according to gender and age. The results may be placed into percentile groups according to gender and age (Table 16.14) [199].

There have been many cognitive, skill, and technique-based tests published for soccer [200]. Ali [200] conducted an extensive review of these tests, many of which failed to provide reliability or validity data. In elite players, tests such as the

Table 16.13 Speed shot shooting percentile norms for female athletes [199]

	Age, year			
Percentile	14	15	16–17	>17, collegiate
99	38	32	37	44
95	25	23	23	35
90	19	20	20	25
85	17	18	18	22
80	16	16	16	21
75	15	15	14	21
70	14	14	13	20
65	13	13	13	19
60	13	12	12	19
55	12	12	12	18
50	11	11	11	17
45	10	10	10	16
40	10	10	9	15
35	10	9	9	14
30	9	9	8	14
25	9	8	7	13
20	8	7	7	12
15	7	7	6	10
10	6	5	4	9
5	4	4	3	8

Table 16.14 Controlled dribbling percentile norms for female athletes [199]

	Age, year			
Percentile	14	15	16–17	>17, collegiate
99	6.9	7.7	5.5	6.9
95	8.4	8.2	8.2	7.6
90	8.8	8.8	8.8	7.9
85	9.1	9.2	9.3	8.1
80	9.4	9.5	9.6	8.3
75	9.6	9.7	9.8	8.5
70	9.8	9.9	9.9	8.7
65	10.1	10.1	10.1	8.9
60	10.3	10.3	10.3	9
55	10.5	10.5	10.5	9.1
50	10.7	10.7	10.7	9.3
45	10.9	10.9	10.9	9.5
40	11.1	11.2	11.3	9.7
35	11.3	11.4	11.5	9.9
30	11.7	11.7	11.8	10.1
25	12	12	12.2	10.4
20	12.3	12.4	12.7	10.7
15	12.6	13	13	11.2
10	13.6	13.7	13.9	11.8
5	18.1	15.8	15	13.8

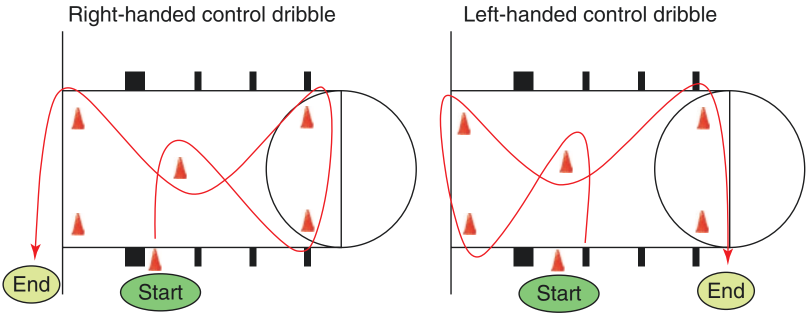


Fig. 16.17 Controlled dribble test course

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 [189]. However, these tests require extensive setup, instruction, and at least two examiners and may not be practical for high school athletes. Two dribbling tests have been proposed and tested in male collegiate and competitive players. McGregor et al. [201, 202] 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. 16.18). 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 ten trials is used as the final score. The validity coefficient is significant for this test ($R = 0.78$, $P < 0.01$).

Haaland et al. [203] 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. [204] 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 [204].

Critical Points

- Field tests should have acceptable reliability in measuring specific functional tasks.
- Explain test and allow practice trials.
- Conduct least fatiguing tests first, including highly skilled tasks (agility or hopping/jumping), and endurance or fatiguing tests last.
- Multistage fitness test. Excellent reliability (ICC ≥ 0.90).
- Yo-Yo test, two levels. Excellent reliability (ICC ≥ 0.90).
- 10-m, 20-m, and 36.6-m sprint tests. Excellent reliability (ICCs >0.90).
- *T*-test. Excellent reliability (ICCs ≥0.90).
- Pro-agility test. Reliability not assessed.
- Service box test (tennis). Excellent reliability (ICC 0.85).
- Vertical jump test. Excellent reliability (ICCs >0.90).
- Sit-up test. Good reliability (ICCs 0.77–1.0).
- Sitting chest pass. Reliability not assessed.
- Medicine ball chest pass, forehand toss, backhand toss, and overhead toss. Significant correlations isometric maximum trunk rotation torque and one-repetition maximum bench press.

16.4 Sports Injury Test

Our nonprofit foundation developed the Sportsmetrics Sports Injury Test to identify some of the risk factors associated with noncontact ACL injuries. This test is available via an App for all Sportsmetrics certified instructors and is currently available for second- and third-generation iPad. The Sports Injury test consists of the

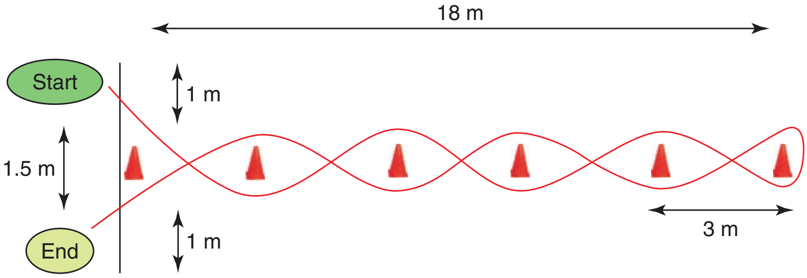


Fig. 16.18 Course for the Loughborough Soccer Dribbling Test

following key components (which are all videotaped): two-legged drop-jump, single-leg squat, and single-leg triple hops. The App assists in calculating knee separation distance on the drop-jump test, knee and hip angles during the single-leg squat test, and knee angles during the hop test. In addition, data may be added for a vertical jump test, 1-min sit-up test, isokinetic tests, 20-yard dash, and VO_2max. The app compiles a report with bilateral comparisons (right and left limbs) and may also include knee examination data, general notes, and recommendations for clinicians.

16.5 Other Testing Considerations

16.5.1 Body Mass Index

Body mass index is calculated as weight (in kilograms)/height (in meters) squared. When used in a multivariate model for risk of noncontact ACL injury in high school and collegiate athletes, increased BMI (in addition to increased anteroposterior knee laxity and having a parent who suffered an ACL injury) was reported in a recent study to be significantly predictive of ACL injury (odds ratio [OR], 1.20; $P = 0.01$) [1]. Uhorchak et al. [205] also reported that a higher than average BMI, along with a narrow femoral notch width and generalized joint laxity, was a significant predictive risk factor in female cadets. Higher than average was defined in that study as 1 standard deviation above the mean value of 22 ± 2 in 118 women aged 17–23 years. The authors postulated that this could have been due to a poorer level of fitness or lower level of activity; however, they acknowledged that those explanations were speculative, and further research was required to understand the relationship between BMI and noncontact ACL injuries.

16.5.2 Femoral Notch Width

Several investigators have reported that a narrow femoral notch width is a risk factor for noncontact ACL injuries in female athletes [205–213], although others have refuted this finding [214, 215]. Magnetic resonance imaging (MRI) provides the most accurate measurement of intercondylar notch width [207]. Plain radiographs provide only a single-plane measurement and not a three-dimensional area of the actual size of the ACL and are inaccurate in measuring actual notch size [216, 217].

16.5.3 Tibial Slope

Several studies have reported potential associations between increases in tibial slope measured either on radiographs or MRI and noncontact ACL injuries [209, 214, 218–230], although MRI techniques more precisely measure knee geometry [225, 226, 228]. One investigation found a significant difference in medial tibial slope between ACL-injured and control knees in pediatric subjects with open physes who were 12–17 years old [214]. Another reported an increase in posterior tibial slope in 45 females who had sustained noncontact ACL injuries compared with 53 controls [230]. Hashemi et al. [224] suggested that a combination of increased posterior-directed tibial plateau slope and shallow medial tibial plateau measured on MRI could be a risk factor for ACL injuries in both men and women. This was in agreement with a study on 90 male collegiate football players that found that increased lateral tibial slope predicted ACL injury (OR, 1.32) [227].

16.5.4 Generalized Joint Laxity

Generalized joint laxity may be a risk factor for noncontact ACL injuries [205, 231, 232]. Pacey et al. [232], in a meta-analysis of 18 studies, reported a statistically significant relationship between generalized joint hypermobility and risk of a knee joint injury during sports and military training, with combined OR ranging from 3.98 to 4.69 ($P < 0.05$). There was a statistically significant increase in the proportion of knee joint injuries in hypermobile participants compared to nonhypermobile athletes ($P < 0.001$).

Although there are several scoring systems available to measure hypermobility [233–235], the Beighton laxity scale is the most commonly used system [236, 237]. This scale assesses for the following joint laxities: passive dorsiflexion of the fifth metacarpophalangeal joint >90°, passive opposition of the thumb to the palmar forearm, hyperextension of the elbows and knees >10°, and forward flexion of the trunk (with knees straight, so that the palms of both hands rest entirely on the floor).

16.5.5 Neurocognitive Performance Testing

Several authors have recently begun to investigate the potential association between neurocognitive performance and noncontact ACL injuries [238–241]. Neurocognitive (cognitive processes and abilities associated with the functioning of cortical and subcortical brain systems [239]) factors such as visual attention, processing speed/reaction time, and dual-tasking may play a role in ACL injury risk. Herman and Barth [239] measured neurocognitive performance with the Concussion Resolution Index (CRI) in 37 healthy recreational athletes who then underwent an unanticipated jump-landing task. Athletes who scored low on the CRI (mean scores, 41th percentile) had significantly altered neuromuscular performance on landing compared with athletes who scored high (mean scores, 78th percentile), including 31% higher peak vertical ground reaction forces and 26% higher peak proximal anterior tibial shear.

Swanik et al. [239] conducted neurocognitive testing using the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) on 160 athletes from 18 universities. All were tested before the start of their athletic season. Eighty athletes (45 women, 35 men) sustained noncontact ACL injuries and were matched with 80 controls for height, weight, age, gender, sport, position, and years of experience at the collegiate level. The test assessed verbal memory, visual memory, processing speed, and reaction time. There were statistically significant differences between the injured and control groups for all variables, with the injured athletes demonstrating slower reaction times ($P = 0.002$), slower processing speeds ($P = 0.001$), lower visual memory scores ($P < 0.001$), and lower verbal memory scores ($P < 0.05$). Compared with previously published normative values for this age group, the scores in the injured athletes ranged from low average to average, indicating diminished function. The authors observed that mild deficits in reaction time and processing speed could make athletes more susceptible to errors or loss of coordination during the complex environment in athletic competition. In addition, the poorer visual and verbal memory scores indicated that these athletes may have difficulty interpreting and handling conflicting information during unanticipated events. Uncertainty or hesitation diminishes muscle activity, which could affect dynamic restraint and increase the risk of a noncontact ACL injury.

Critical Points

- Body mass index >24 in females aged 17–23 years was a risk factor for ACL injury in one study.
- Narrow femoral notch width is also probably a risk factor.
- Generalized joint laxity important: significant increase knee joint injuries in hypermobile patients.
- Neurocognitive testing: possible correlation increased risk of ACL injuries and requires further study.

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Part III

ACL Injury Prevention Programs

17

Sportsmetrics ACL Intervention Training Program: Components and Results

Frank R. Noyes and Sue Barber-Westin

Abstract

This chapter provides the historical background of the Sportsmetrics ACL intervention training program, which was the first ACL ligament intervention program for female athletes to be published in the peer-reviewed orthopedic literature. The program focuses on decreasing landing forces and improving lower limb alignment from a valgus position to a neutral position by teaching neuromuscular control of the lower limb and increasing knee and hip flexion angles. The dynamic warm-up, plyometric jump training, strengthening, and flexibility components are described and illustrated in detail. The results of numerous research investigations documenting improvements in neuromuscular indices and ACL injury rates are provided.

17.1 Introduction

The Sportsmetrics training program represents the first knee ligament intervention program for female athletes to be published in the peer-reviewed orthopedic literature [1]. Multiple studies have been conducted to scientifically justify the program's ability to reduce the incidence of noncontact anterior cruciate ligament (ACL) injuries, improve deficiencies in neuromuscular indices, and enhance athletic performance indicators. The results of these studies are presented later in this chapter. The program was developed in 1994 during the time period in which the concept of plyometrics was initially introduced to improve athletic performance. We sought to learn of the potential effectiveness of applying some of the theories behind plyometrics into a knee ligament injury prevention program for female athletes. One of the working hypotheses at that time for the explanation of the high rate of ACL injuries in female athletes was poor body mechanics during jumping and landing (the so-called "wiggle-wobble" knee). While no one had yet to fully study the differences in landing mechanics between genders, the senior author empirically noted that women tended to land from a jump with their knees close to full extension or in a valgus position. There was also the knowledge that female athletes had weak hamstrings from clinical experience. The question was raised if a

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plyometric-based training program could improve these landing mechanics and increase hamstrings strength.

Sportsmetrics was created, with special emphasis placed on decreasing landing forces and improving lower limb alignment from a valgus position to a neutral position by teaching neuromuscular control of the lower limb. The initial program implemented these concepts along with strength training (lower extremity, upper extremity, and core) and flexibility [1]. The 6-week program was tested in a few local high schools to determine if the training could be successfully accomplished and what challenges would be incurred on a small scale. The results were encouraging and justified the need to determine if Sportsmetrics training could alter the kinematics and kinetics of the knee and lower extremity during landing and reduce the incidence of knee ligament injuries in female athletes. Later studies also examined the effectiveness of sports-specific training programs on improving athletic performance indicators such as speed, agility, and aerobic conditioning [2–6].

The components of the Sportsmetrics neuromuscular training program include a dynamic warm-up, plyometric jump training, strengthening, and flexibility. It is recommended that the program be conducted either during the off-season or just before the sport season begins. Training is accomplished three times a week on alternating days for 6 weeks either in classes led by an instructor who has completed certification training from the authors' Center (see sportsmetrics.org) or from an instructional step-by-step videotape series. Athletes who do not train with a certified instructor are encouraged to train either in front of a mirror or with a partner so that mistakes in technique, form, and body alignment may be detected and corrected.

The Sportsmetrics program described in this chapter and the sports-specific programs described in Chap. 18 were created at the non-profit Cincinnati SportsMedicine Research and Education Foundation under the direction of the senior author. Many researchers, trainers, scientists, and clinicians were involved in the various stages of development of these programs, and it is with tremendous gratitude that the authors acknowledge their efforts:

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Critical Points

- Sportsmetrics: first published knee ligament intervention program for high school female athletes.
- Program focuses on decreasing landing forces, improving lower limb alignment by teaching neuromuscular control of the lower limb, and increasing knee and hip flexion angles.
- Components: dynamic warm-up, jump training, strength training, and flexibility.
- Conduct preseason or off-season, 3 days/week for 6 weeks.
- Original program and sports-specific programs available.

17.2 Training Concepts: Internal Versus External Focus Cues

Verbal feedback during training is essential and is usually directed on a conscious focus on movements of the body, which is termed *internal focus* [7, 8]. An example of an internal focus cue would be to tell an athlete to "jump as high as possible and keep your attention on extending your legs as rapidly as possible" during a countermovement vertical jump. A different method of motor learning, termed *external focus*, directs attention

Table 17.1 Examples of internal and external focus cues

Jump	Internal focus cues	External focus cues
Squat jump	• Keep shoulders back and chest lifted	• Position 2 cones in front of the athlete hip-distance apart: point knees and toes toward the cone on landing
	• Hips should sit lower than shoulders and back behind the heels on the squat	• Reach hands toward the cones during the squat
	• Keep toes, knees, and hips in line	• Reach hands toward the ceiling on every jump
	• No wiggle wobble in knees	• Pretend going to sit in a chair when coming down into the squat
	• Fully extend the body on the reach	• Imagine holding a ball between knees throughout the entire jump
	• Land on the ball of the foot and quickly rock back to the heels going into the squat	
	• Keep head up	
Barrier jump	• Land on the ball of the foot and rock back to the heel	• Position 2 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
	• No wiggle wobble in knees	• Tuck the knees to clear the barrier
	• Tuck the knees up to the chest	• Imagine a ball being held between the knees to maintain neutral alignment
	• 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	
Broad jump	• Keep hips, knees, and ankles in line (hip distance) as you take off and land	• Imagine a ball in between the legs during entire jump to maintain hip distance
	• Stay low in landing with shoulders up and hips lower than shoulders	• Position 2 cones in front of the athlete hip-distance apart: point knees and toes toward the cone on landing
	• Land on the balls of the feet and quickly rock back to the heels	• Use cones as a goal to jump to
	• Look up	• Imagine sitting in a chair in order to stay low in landing
	• No wobbly knees	• Reach down toward the cone to lower the body into a squat position
		• Focus eyes upward toward the instructor
Single-leg hop	• Keep the hip, knee, and ankle neutral	• Quiet landing, land light as a feather
	Don't allow the knee to cave inward	• Position a cone a few feet in front of the athlete: point knee and toe toward a cone
	• Land on the ball of the foot, rock back to the heel	• Use cone as goal for hop distance
	• Keep eyes focused upward	• Look up at the instructor
	• Get low into a squat on landing	• On landing, imagine sitting in a chair on one leg
	• Hips shift back and sit low, back is upright, shoulders should be higher than hips	

toward the result of the movement. An example would be to attach a ball to the ceiling and instruct the athlete to "jump up as high as possible and keep your attention on jumping as close to the ball as you can" [9]. The basic hypothesis proposed by Wulf et al. [10] is that an internal focus cue causes an athlete to control movements at a conscious level that may constrain the motor system's natural, automatic control mechanisms that allow movements to be done effectively and efficiently. Conversely, external focus cues induce greater automaticity in movement control that uses unconscious, fast, and reflexive control processes (Table 17.1).

In regard to athletic performance, multiple studies have demonstrated that, compared with internal focus (or control) cues, external focus instruction results in significant improvement in performance in vertical jump height [9, 11–13] and standing long jump distance [11, 14–16], as well as accuracy in movement and skills in golf [17, 18], basketball [19], volleyball [20], and soccer [21].

The issue of applying external focus training cues during neuromuscular training in order to further enhance improvements in potentially dangerous neuromuscular body positions during landing, cutting, and pivoting is valid to consider [22]. In a study with 36 physically active male collegiate students, Makaruk et al. [11] conducted 9 weeks of plyometric training using either external focus, internal focus, or control cues. The data revealed that only the external focus group had significant increases in knee flexion on a drop-jump and countermovement vertical jump. A novel study performed in patients ≥4 months post-ACL reconstruction determined whether differences occurred in the single-leg hop test in distance and knee kinematic variables between patients who received internal focus cues and those who received external focus cues [23]. Compared with the internal focus group, the external focus group had significantly larger knee flexion angles at initial contact (37.38° ± 6.44° and 27.25° ± 11.09°, respectively, $P = 0.04$), peak knee flexion (69.54° ± 11.44° and 51.75° ± 16.67°, respectively, $P = 0.01$), total range of motion (32.16° ± 7.36° and 24.50° ± 6.92°, respectively, $P = 0.05$), and time to peak flexion (0.21 ± 0.03 s and 0.16 ± 0.05 sec, respectively, $P = 0.02$). Although the external focus group jumped 6–11 cm further than the internal focus group, the results were not statistically significant. The investigators recommended the implementation of external focus cues to enhance safer movement patterns after ACL reconstruction.

We have integrated 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; a complete listing of all of these cues is available on a DVD at sportsmetrics.org.

17.3 Components

17.3.1 Dynamic Warm-Up

The dynamic warm-up prepares the body for rigorous training with functional-based activities that incorporate various motions of the upper and lower extremities and core. The brief warm-up should raise core body temperature, increase heart rate, increase blood flow to the muscles, and assist balance and coordination. The exercises are performed across the width of a court or field or for approximately 20–30 s.

17.3.1.1 Toe Walk

Walk on the toes and keep the legs straight (Fig. 17.1). Do not allow the heel to touch the ground. Keep the hips neutral during the entire exercise.

17.3.1.2 Heel Walk

Walk on the heels and keep the legs straight (Fig. 17.2). 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.

17.3.1.3 Straight Leg March

Walk with both legs straight, alternating lifting up each leg as high as possible without compromising form (Fig. 17.3). Keep the knees straight and the posture erect. Do not lean backward.

Fig. 17.1 Toe walk

Fig. 17.2 Heel walk

Fig. 17.3 Straight leg march

17.3.1.4 Leg Cradle

Walk forward and keep the entire body straight and neutrally aligned. Lift one leg off of the ground in front of the body, bending at the knee (Fig. 17.4). Turn the knee outward and grasp the foot with both hands. Hold this position for 3 s, then place the foot back down, and repeat with the opposite leg.

17.3.1.5 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. 17.5). 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.

Fig. 17.4 Leg cradle

17.3.1.6 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. Immediate 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.

17.3.1.7 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.

17.3.1.8 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.

17.3.1.9 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

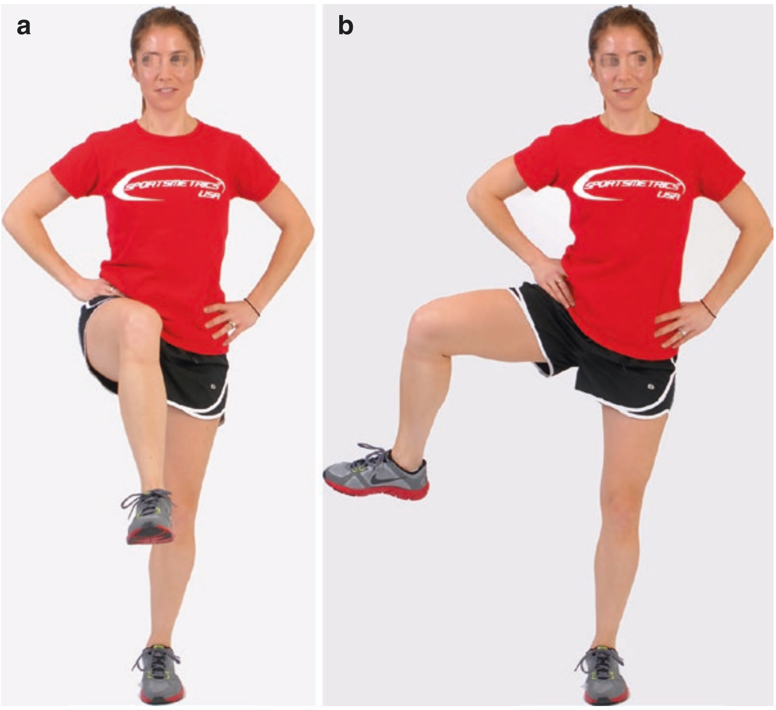

Fig. 17.5 (**a**, **b**) Dog and bush walk

complete circle with the legs. Stay up on the balls of the feet throughout the exercise.

17.3.1.10 All-Out Sprint

Sprint forward as fast as possible, making sure to maintain proper technique and running form.

17.3.2 Plyometrics/Jump Training

Plyometrics assist in developing muscle control and strength considered essential to reduce the risk of knee ligament injuries. These exercises enhance muscular power, vertical jump height, acceleration speed, and running speed [24–28]. However, if done improperly, plyometrics are not to be expected to have a beneficial effect in reducing the risk of a noncontact ACL injury. Therefore, the philosophy regarding this component of the Sportsmetrics program is to emphasize and teach correct jumping and landing techniques throughout the 6 weeks of training. Specific drills and instruction are used 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 jumping drills (to instill correct form) to multi-directional, single-foot hops and plyometrics with an emphasis on quick turnover (to add movements that mimic sports-specific motions). The jump training is divided into three 2-week phases, each of which has a different training focus and exercises (Table 17.2).

Phase I (technique development phase) focuses on teaching 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

Table 17.2 Sportsmetrics neuromuscular training program: jump training component

Jumps	Duration	
Phase I: 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 II: 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 III: 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 duration or repetitions listed

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 and mirrors, when available, are used to provide visual feedback. 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.

Phase II (fundamentals phase) continues emphasis on proper techniques. Athletes continue to perform six of the jumps from phase I but for longer periods of time. In addition, three new jumps are incorporated. Phase III (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.

17.3.2.1 Wall Jump

Instruction: This jump is always performed first to prepare the athlete mentally and physically for plyometric training. This also provides the instructor with the opportunity to observe and begin 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 straight forward.

Common problems: Slouched posture, excessive knee flexion, head down, and eyes watching the feet.

Corrections: Keep the eyes and head focused up, keep the knees slightly bent, and land softly.

17.3.2.2 Tuck Jump

Instruction: Begin standing with the feet shoulder-width apart. Jump up and bend the knees upwards together up toward the chest as high as possible (Fig. 17.6). 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 takeoff 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 throughout the jump, and the back should be straight, and the eyes looking up.

17.3.2.3 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. An external focus cue to use is to position two cones in front of the athlete hip-distance apart; point the knees and toes toward the cone on landing (Fig. 17.7).

Common problems: Landing with body or knees forward, being off-balance, bringing the knees together during takeoff 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 takeoff and landing, keep the knees and ankles shoulder-width apart, and keep the back straight, and the head and eyes up.

17.3.2.4 Barrier Jump Side-to-Side

Instruction: A cone or barrier approximately 6–8 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 in the same amount of knee flexion as the starting position. An external focus cue to use is to position two cones in front of the athlete hip-distance apart; point the knees and toes toward the cone on landing (Fig. 17.8).

Common problems: Starting or landing with stiff, straight, or wobbly knees; not bringing the entire body over the barrier; double-bouncing on

Fig. 17.6 (**a**, **b**) Tuck jump

Fig. 17.7 Squat jump with external focus cue

landing and takeoff; 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.

17.3.2.5 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.

17.3.2.6 180° 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. 17.9). Hold the landing for 2-3 s, and then reverse the direction and repeat the jump.

Fig. 17.8 (**a**–**c**) Barrier jump side-to-side with external focus cue

Fig. 17.8 (continued)

Fig. 17.9 (**a**–**c**) 180° jump

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.

17.3.2.7 Broad Jump

Instruction: Begin with the knees deeply flexed, and 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. An external focus cue to use is to position two cones in front of the athlete hip-distance apart; point the knees and toes toward the cone on landing and use them as a goal to reach (Fig. 17.10).

Common problems: Not holding or sticking the landing, letting the knees collapse inward during landing and takeoff, landing with little knee flexion or in an upright position, and using a slouched posture.

Corrections: Keep the knees over the heels and under the hips on takeoff 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.

17.3.2.8 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. 17.11). 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.

17.3.2.9 Jump, Jump, Jump, Vertical Jump

Instruction: The exercise begins with three consecutive broad jumps, using deep knee flexion for each takeoff and landing. Immediately after landing the third jump, a maximum vertical jump is performed and then the deep crouch position used for the final landing, which is held for 5 s.

Common problems: Allowing the knees to collapse inward during landing and takeoff and carrying the body forward rather than up on the vertical jump.

Corrections: Keep the knees over the heels and under the hips on takeoff 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.

17.3.2.10 Barrier Hop Side-to-Side, Single Leg

Using the same cone or barrier from phase I, a single-leg hop side-to-side over the barrier is performed.

17.3.2.11 Barrier Hop Forward-Backward, Single Leg

Using the same cone or barrier from phase I, a single-leg hop forward and backward over the barrier is performed (Fig. 17.12).

17.3.2.12 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. 17.13), and land with the opposite leg bent in front. Alternate the legs with each jump.

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 body, landing

Fig. 17.10 (**a**, **b**) Broad jump with external focus cue

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.

17.3.2.13 Single-Leg Hop

Instructions: This hop is similar to the broad jump, except the athlete begins and lands on the one leg. The landing in a deep crouched position is held for 5 s. An external focus cue to use is to position a cone a few feet in front of the athlete; point the knee and toes toward the cone on landing and use it as a goal to reach (Fig. 17.14).

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.

Fig. 17.11 (a–c) Bounding in place

Fig. 17.12 (**a**–**c**) Barrier hop forward-backward

17.3.2.14 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.

17.3.2.15 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 of 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.

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.

17.3.2.16 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. 17.15).

Common problems: Landing with unstable knees or knees collapsed inward, double-bouncing on landing, and landing with feet staggered.

Fig. 17.13 (**a**–**c**) Scissor jump

Fig. 17.14 (**a**, **b**) Single-leg hop with external focus cue

Fig. 17.15 (**a**–**c**) Mattress jump side-to-side

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.

17.3.2.17 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.

17.3.2.18 Hop, Hop, Hop, Stick

Perform three single-leg hops for distance and hold the final landing for 5 s. The common problems and corrections are those described for the single-leg hop.

17.3.2.19 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.

17.3.3 Strength Training

A combination of exercises is recommended to develop upper extremity, lower extremity, and core to improve overall muscular efficiency. Either weight equipment or free weights may be used based on 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.

17.3.3.1 Mini-squats with Resistance Band

Instructions: Stand on the center of a strip of resistance band with the feet shoulder-width apart (Fig. 17.16), 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.

Fig. 17.16 (**a, b**) Mini-squat with resistance 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.

17.3.3.2 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. 17.17). 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.

17.3.3.3 Prone Hamstrings with Partner Resistance

Instructions: The athlete performing the exercise lie flats 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 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. 17.17 Lunge with external focus cue

Common problems: The upper body or working hip lifts off the ground, and the partner does not provide enough resist 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.

17.3.3.4 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. 17.18). 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 I.

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.

17.3.3.5 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 II.

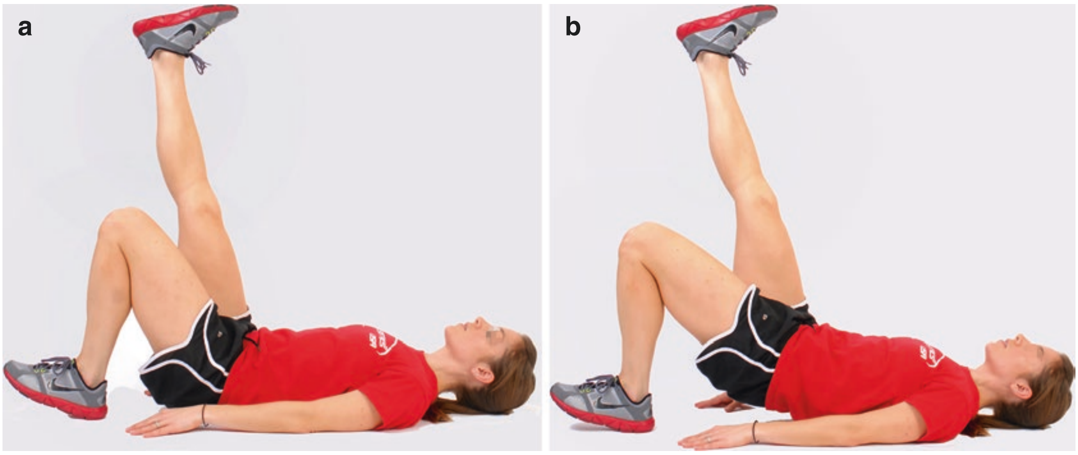

Fig. 17.18 (**a**, **b**) Supine hamstrings bridge

17.3.3.6 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 III.

17.3.3.7 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. 17.19). 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.

17.3.3.8 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. 17.20). Extend the toes and fingers on the lifted extremities and keep the abdominals tight. Perform for 30 s during weeks 1–3 and 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.

17.3.3.9 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. 17.21). Perform 1 day each week for 30 s in phase I, 60 s in phase II, and 90 s in phase III.

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.

Fig. 17.19 (**a**, **b**) Arm swing with resistance band

Fig. 17.20 (**a**, **b**) Abdominals (Superman)

Move the torso as a unit and touch the ground with the hands with each rotation.

17.3.3.10 Abdominals (Plank)

Instructions: Lie face down and position the elbows under the shoulders with the forearms on the floor (Fig. 17.22). 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 I, 60 s in phase II, and 90 s in phase III.

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.

17.3.3.11 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 possible (Fig. 17.23). Perform 1 day each week for 30 s in phase I, 60 s in phase II, and 90 s in phase III.

Common problems: The shoulders are not kept off of the ground, the upper body rotates, and the legs are moved close to body.

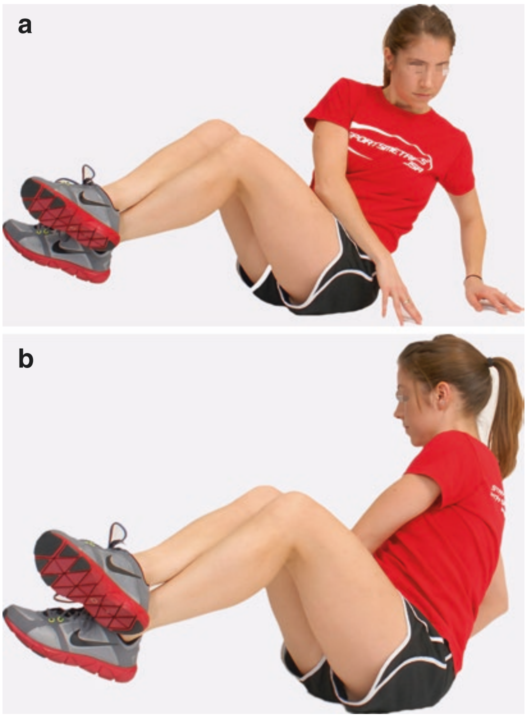

Fig. 17.21 (**a**, **b**) Abdominals (Russian twists)

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.

17.3.3.12 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. 17.24). 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 2 sets of 10 repetitions, with 30 s of rest between each set. A third set of 20 repetitions is done in phase I, 30 repetitions in phase II, and 40 repetitions in phase III.

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.

17.3.3.13 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. 17.25). Begin with the feet shoulder-width apart, with one knee slightly bent so that the foot is off of the ground. Balance on the other leg and kick the

Fig. 17.22 Abdominals (plank)

Fig. 17.23 (**a**, **b**) Abdominals (bicycle kicks)

Fig. 17.24 (**a**, **b**) Hip flexor resistance band kicking

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 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.

17.3.3.14 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. 17.26). Step far enough to pro-

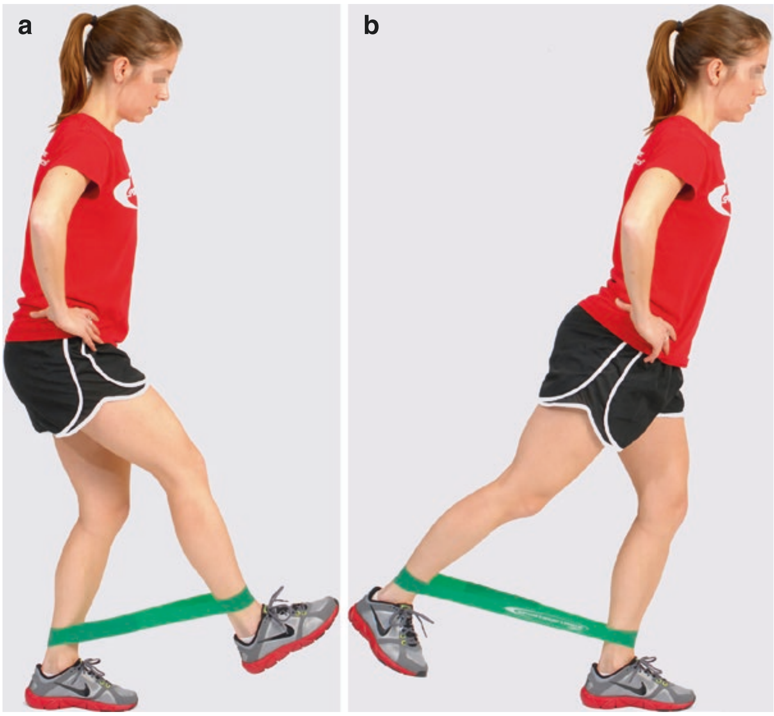

Fig. 17.25 (**a**, **b**) Steamboats

Fig. 17.26 (**a**, **b**) Hip abductor resistance band kicking

duce moderate tension in the band, and then kick the outside leg sideways against the resistance of the band. Perform 2 sets of 10 repetitions, with 30 s of rest between sets. A third set of 20 repetitions is done in phase I, 30 repetitions in phase II, and 40 repetitions in phase III.

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.

17.3.3.15 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. 17.27). Begin with the foot shoulder-width apart. Step out with one feet 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 to 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. 17.27 (**a, b**) Lateral walking with resistance band

17.3.4 Flexibility

Stretching exercises are important to achieve 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.

17.3.4.1 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. 17.28). 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 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.

17.3.4.2 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 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. 17.29). This stretch may be done lying on the back to support the spine and neck.

17.3.4.3 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. 17.30).

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 and straight up, keep the back straight, the shoulders back, and the head up.

17.3.4.4 Hip Flexor

Instructions: Begin in a lunge position with the front knee slightly bent (Fig. 17.31). 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.

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.

Fig. 17.28 Hamstrings stretch

Fig. 17.29 Iliotibial band stretch

Fig. 17.30 Quadriceps stretch

Fig. 17.31 Hip flexor stretch

Fig. 17.32 Gastrocnemius stretch

17.3.4.5 Gastrocnemius

Instructions: Begin in a long lunge position with the front knee slightly bent, but not extended past the ankle (Fig. 17.32). 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.

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.

17.3.4.6 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.

17.3.4.7 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. 17.33). Keep the shoulders relaxed and the head, neck, and neutral.

Fig. 17.33 Deltoid stretch

17.3.4.8 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. 17.34).

17.3.4.9 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. 17.35).

17.3.4.10 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 further away from the body. Do not rise up from the heels (Fig. 17.36).

Fig. 17.34 Triceps, latissimus dorsi stretch

Critical Points

- Dynamic warm-up: ten exercises to prepare the body for rigorous training.
- Plyometric/jump training: philosophy – teach correct jumping and landing techniques throughout 6 weeks of training.
  - Three phases: technique development, fundamentals, performance
  - Constant verbal cues, feedback
  - 7–9 jumps per session
- Strength training for upper extremity (deltoids, pectorals, triceps, latissimus dorsi/low back), lower extremity (quadriceps, hamstrings,

Fig. 17.35 Pectoralis, biceps stretch

Fig. 17.36 Low back stretch

gluteals, and gastrocnemius), and core to improve overall muscular efficiency.
  - Combination exercises with either weight machines, free weights, body weight, or resistance band
- Flexibility: hamstrings, iliotibial band, quadriceps, hip flexor, gastrocnemius, soleus, deltoid, triceps, biceps, pectoralis, and latissimus dorsi.

17.4 Research Investigations

17.4.1 ACL Injury Reduction

At the time of writing, 847 high school female athletes had completed Sportsmetrics training at our Center. Compared with a control group of 1216 female athletes, the trained group had a significant reduction existed in noncontact ACL injury rates ($P = 0.026$, Table 17.3).

Historically, we first determined the effectiveness of Sportsmetrics training in a controlled prospective investigation in 1263 high school soccer, volleyball, and basketball athletes [29]. There were two groups studied: 366 females that underwent 6 weeks of traditional Sportsmetrics training, 463 females from 15 teams that did not undergo training, and 434 male athletes from 13 teams who also did not undergo training. All athletes were followed throughout a single season for injuries. The total number of athlete-exposures (AEs) were 17,222 for the trained group, 23,138 for the female control group, and 21,390 for the male control group. The relative noncontact knee ligament injury incidence per 1000 AEs was 0 in the trained group, 0.35 in the female control group, and 0.05 in the male control group. A significant difference was found between the trained and untrained groups ($P = 0.05$).

17.4.2 Changes in Neuromuscular Indices

It is well recognized that, during athletic tasks, differences exist between female and male athletes in movement patterns; muscle strength, activation, and recruitment patterns; and knee joint stiffness under controlled, preplanned, and reactive conditions in the laboratory. Many investigators believe these neuromuscular and biomechanical factors are at least partially responsible for the disparity between genders in noncontact ACL injury rates. Studies conducted at our laboratory and those of others have demonstrated that the Sportsmetrics program is effective in inducing desired changes in neuromuscular indices in female athletes.

Table 17.3 Effect of Sportsmetrics training on reduction of noncontact ACL injury rates in high school female athletes

	No. athletes	No. athlete-exposures	No. noncontact ACL injuries	Injury rate per 1000 athlete-exposures	*P* value	Incidence rate ratio 95% confidence interval
Trained group	847	45,351	1	0.02	**0.026**	0.08 (0.002–0.49)
Control group	1216	66,812	19	0.28		

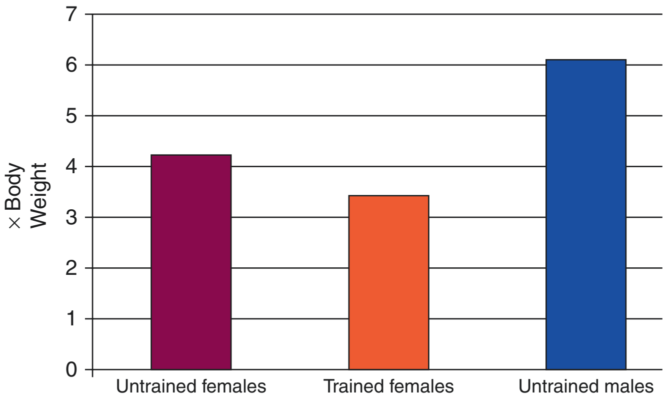

Fig. 17.37 Peak landing forces in 11 female subjects before and after Sportsmetrics training and in 9 male control subjects. There was a significant difference between untrained females and trained females and between males and both female groups ($P < 0.01$) [1]

A laboratory study was conducted at our center with high school female volleyball players to determine the effect of Sportsmetrics training on landing mechanics and lower extremity strength [1]. A control group of male subjects was matched with the females for height, weight, and age. The female athletes underwent a series of tests before and after Sportsmetrics training that included vertical jump height, isokinetic lower extremity muscle testing at 360°/s, and force analysis testing with a two-camera, video-based, optoelectronic digitizer for measuring motion and a multicomponent force plate for measuring ground reaction force and abduction and adduction moments.

The training program effectively decreased peak landing forces from a block jump by 22% ($P = 0.006$) or an average of 456 N (103 pounds). All but one of the female subjects showed a decrease in these forces (Fig. 17.37). Knee abduction and adduction moments decreased approximately 50% (Fig. 17.38). Trained female athletes had lower peak landing forces than male athletes and lower adduction and abduction moments after training compared with pre-training values. Decreased abduction or abduction moments may lessen the risk of lift-off of the medial or lateral femoral condyle,

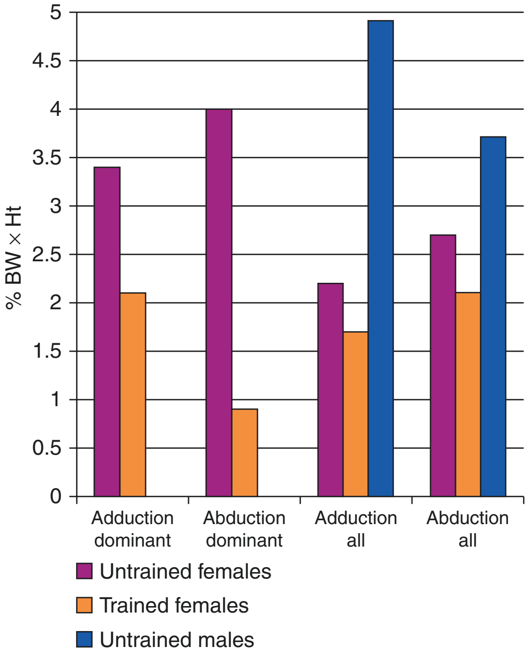

Fig. 17.38 Peak knee adduction and abduction moments on landing from a vertical jump. The 22 female subjects were grouped according to the dominant moment (adduction or abduction) and were also grouped together (All). In the dominant subgroups, the trained females had significantly smaller adduction 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 ($P < 0.05$) [1]

improve tibiofemoral contact stabilizing forces [30], and reduce the risk of a noncontact ACL injury.

Significant increases in isokinetic knee flexion peak torque and the hamstring-to-quadriceps (H:Q) ratio following Sportsmetrics training were reported in several investigations (Table 17.4) [1, 3, 31, 32].

Sportsmetrics training has effectively improved overall lower limb alignment in the coronal plane in several investigations [3–6, 31]. Statistically significant improvements were found in the absolute and normalized knee and ankle separation distances for all phases (preland, land, takeoff) of the jump-land sequence ($P < 0.001$). Figure 17.39 shows an example of the overall lower limb alignment of a female athlete during the takeoff sequence of the drop-jump test. The absolute knee separation distance of 17 cm before training improved to 37 cm after Sportsmetrics training.

In one investigation [33], female high school volleyball players underwent the video drop-jump test and then completed the Sportsmetrics Volleyball program. The athletes repeated the drop-jump test immediately upon completion of 6 weeks of training and then 3 and 12 months later. Significant improvements were found in the mean normalized knee separation distance between the pre- and post-trained values for all test sessions ($P < 0.01$). Immediately after training, 11 athletes (69%) displayed significant improvements in the mean normalized knee separation distance that were retained 12 months later. Eight of these 11 subjects showed a continued improvement in their normalized knee separation distance over the three post-training test sessions (Fig. 17.40). There were three athletes who had smaller normalized knee separation distance values at the immediate post-trained test compared to the pre-trained test but then improved at the 3- and 12-month post-trained tests (Fig. 17.41). Five athletes failed to improve their overall lower limb alignment on this test during the course of the study. These athletes were encouraged to continue neuromuscular and strength training within the allowance of their volleyball training and season participation.

Table 17.4 Significant improvements from Sportsmetrics training in female athletes

Number athletes trained, study citation	Factor	Pre-train[a]	Post-train[a]	*P* value
Lower limb alignment drop-jump (knee separation distance)				
912 high school athletes [3]	Absolute (cm) Normalized (%)	20 ± 8 47 ± 19	27 ± 8 65 ± 17	<0.0001 <0.0001
62 high school athletes [31]	Absolute (cm) Normalized (%)	23 ± 9 51 ± 19	29 ± 8 68 ± 18	<0.001 <0.001
34 high school volleyball [4]	Absolute (cm) Normalized (%)	21 ± 8 56 ± 19	26 ± 5 63 ± 13	0.002 0.04
57 high school basketball [5]	Absolute (cm) Normalized (%)	18 ± 7 45 ± 17	32 ± 10 74 ± 19	<0.0001 <0.0001
62 high school soccer [6]	Absolute (cm) Normalized (%)	15 ± 4 36 ± 7	23 ± 6 54 ± 14	<0.0001 <0.0001
Isokinetic knee flexion peak torque (300°/s, Nm/body weight)				
141 high school athletes [3]	Dominant leg Nondominant leg	29 ± 6 27 ± 6	33 ± 8 31 ± 7	<0.0001 <0.0001
62 high school athletes [31]	Dominant leg Nondominant leg	40 ± 8 38 ± 8	44 ± 7 42 ± 8	<0.0001 <0.0001
Isokinetic hamstrings/quadriceps ratio (300°/s)				
141 high school athletes [3]	Dominant leg Nondominant leg	83 ± 17 78 ± 18	90 ± 24 83 ± 19	0.001 0.006
62 high school athletes [31]	Nondominant leg	73 ± 15	83 ± 15	0.001

[a] Values are mean ± standard deviation

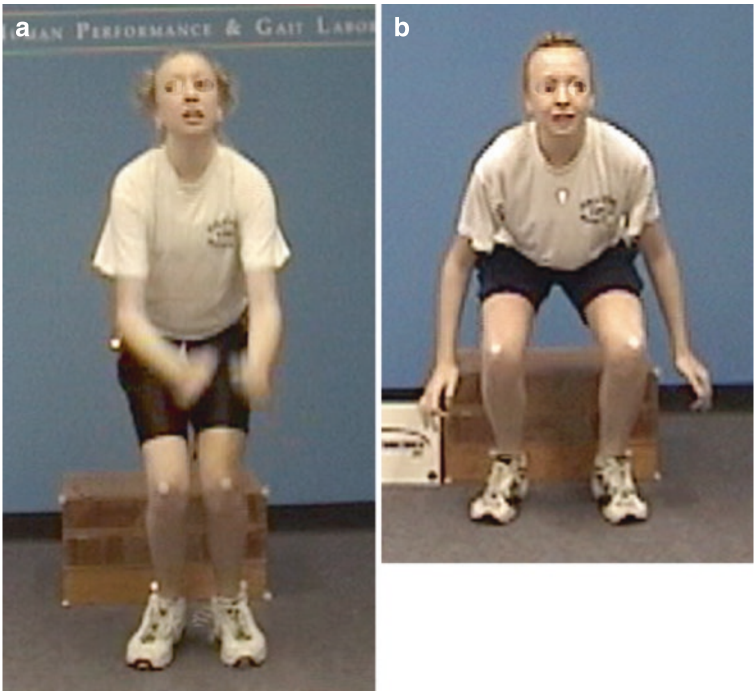

Fig. 17.39 The video drop-jump takeoff sequences from a 14-year-old female basketball player before and after neuromuscular training. (**a**) Before training, the athlete demonstrated poor absolute knee separation distance of 17 cm. (**b**) After training, a marked improvement in knee separation distance of 37 cm is evident (From Noyes FR, Barber-Westin SD, Fleckenstein C, Walsh C, West J (2005): The drop-jump screening test: Difference in lower limb control between gender and effect of neuromuscular training in female athletes. Am J Sports Med 33: 197–207)

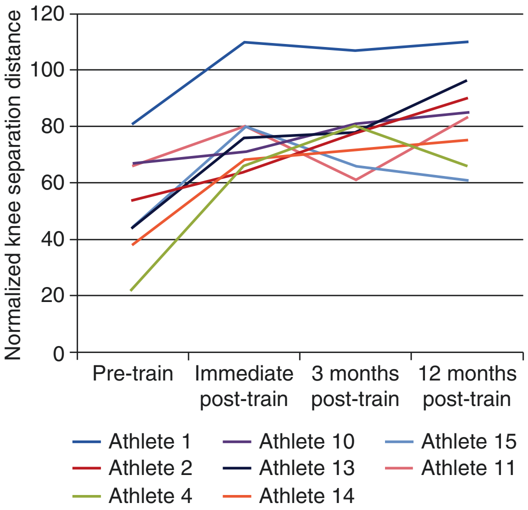

Fig. 17.40 Eight athletes who demonstrated improvements in normalized knee separation distance values at all time periods compared to the pre-train values

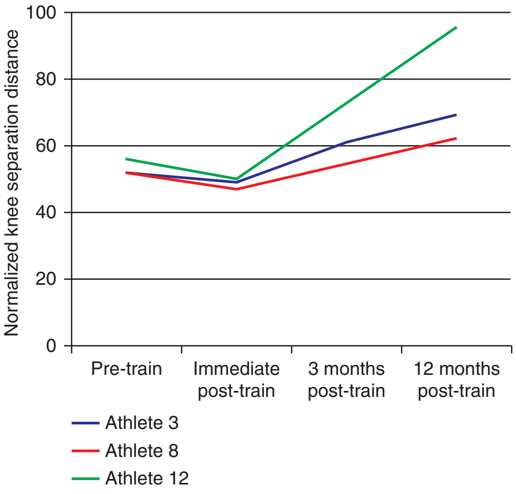

Fig. 17.41 Three athletes who had smaller normalized knee separation distance values at the immediate post-trained test compared to the pre-trained test but who then improved at the 3- and 12-month post-trained tests (From Barber-Westin SD et al.: The drop-jump video screening test: retention of improvement in neuromuscular control in female volleyball players. J Strength Cond Res 24: 3055–3062, 2010)

17.4.3 Gender Disparity Investigations

We measured differences between genders and the effect of Sportsmetrics training on lower limb alignment on a drop-jump test (Table 17.5) [31]. The study involved 325 untrained females, 62 trained females, and 130 untrained males aged 11 to 19 years of age. There was no significant difference between untrained female and male subjects for knee and ankle separation distance on landing. A marked decrease in knee separation

Table 17.5 Conclusions from Sportsmetrics gender comparison studies

Study citation	Factor, no. athletes tested, age	Effect of gender	Effect of age	Conclusions
Noyes [31], Barber-Westin [34]	Lower limb alignment drop-jump test 396 untrained females 62 trained females 140 untrained males Aged 9–17 years	No effect knee separation distance Distinct valgus lower limb alignment 77% of females, 72% of males	Females: no effect ankle, knee separation distance Males: Ankle separation distance greater in subjects aged 9–12 years than those aged 13–17 years	Significant increases knee, ankle separation distances after training Post-trained knee, ankle separation distances in females significantly greater than untrained males Not all females improve, further training may be required Use test as screening tool, useful to educate athletes on body positioning and mechanics during drop-jump
Barber-Westin [34]	Quadriceps, hamstrings isokinetic peak torque (300°/s) 853 untrained females 177 untrained males Aged 9–17 years	No effect athletes 9–13 years Males ≥14 years significantly greater quadriceps, hamstrings than age-matched females	Females: 20% increase quadriceps 9–13 years, 16% increase hamstrings 9–11 years, no increases thereafter Males: 38% increase quadriceps 9–14 years, 23% increase hamstrings 9–14 years	Significant increases quadriceps dominant and nondominant limbs with age. Only slight increases in hamstrings with age
Barber-Westin [34]	Hamstrings: quadriceps ratio 853 untrained females 177 untrained males Aged 9–17 years	No effect	Females: Non-significant decline with age Males: Significant decline from 9 to 14 years	Significant improvements nondominant leg only
Barber-Westin [34]	Limb symmetry single-leg timed side hop, cross-over hop for distance 247 untrained females 77 untrained males Aged 9–17 years	No effect either test except males 15 years had greater mean limb symmetry on cross-over hop than age-matched females	Females: No effect either test Males: No effect on either test	No correlation limb symmetry and isokinetic quadriceps, hamstrings peak torques
Noyes [35]	Internal, external tibial rotation isokinetic strength (120, 180°/s) 47 untrained females 47 untrained males Aged 11–17 years	No effect all athletes 9–13 years Males 14–17 years significantly greater internal rotation peak torque (17%), time to peak torque (28%) than age-matched females	Females: no effect Males: 14–17 years greater internal (17%) and external (14%) rotation peak torques than 11–13 years	Ratios internal, external rotation peak torques to hamstrings avg 26–30% Ratios internal and external rotation peak torques to quadriceps avg 20–22%

distance (≤ 60%), or a valgus alignment appearance (Fig. 17.42), was found in 80% of females and 72% of males. After Sportsmetrics training, significant increases were noted in the knee separation distance in the female athletes (Fig. 17.43).

We conducted an investigation on prepubescent athletes to determine if differences existed between genders in knee separation distance on the drop-jump test, lower limb symmetry on single-leg hop tests, and lower limb isokinetic muscle strength [36]. The study involved 27 female and 25 male athletes aged 9–10 years who were matched for body mass index and years of organized sports participation. There was no difference between the boys and girls in the percentage of athletes who demonstrated a notable valgus alignment. There were no differences between boys and girls in quadriceps and hamstrings peak torques, hamstrings/quadriceps ratio, time to peak torque, total work, or lower limb symmetry values. The conclusion was reached that a high percentage of male and female athletes had a notably valgus lower limb alignment during the drop-jump test and a lack of symmetry between limbs in single-leg hop tests. Consideration is warranted for neuromuscular training in these young athletes to improve landing mechanics, body positioning, balance, and muscle strength.

Fig. 17.42 The drop-jump takeoff sequence for a 12-year-old male soccer player who demonstrates poor knee separation distance of 10.6 cm (From Noyes FR, Barber-Westin SD, Fleckenstein C, Walsh C, West J: The drop-jump screening test: Difference in lower limb control between gender and effect of neuromuscular training in female athletes. Am J Sports Med 33: 197–207, 2005)

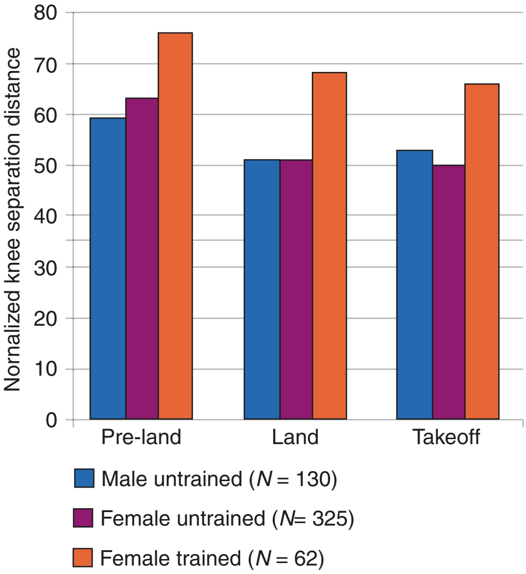

Fig. 17.43 The mean normalized knee separation distances for the three phases of the drop-jump test are shown for the male athletes, untrained female athletes, and trained female athletes. After training, female athletes had statistically significant increases in the mean normalized knee separation distance in all three phases ($P < 0.001$) and had statistically greater mean normalized knee separation distances than males for all phases ($P < 0.0001$) (From Noyes FR, Barber-Westin SD, Fleckenstein C, Walsh C, West J: The drop-jump screening test: Difference in lower limb control between gender and effect of neuromuscular training in female athletes. Am J Sports Med 33: 197–207, 2005)

We assessed the effects of chronological age and gender in a larger number of athletes aged 9–17 years on isokinetic lower extremity strength, lower limb alignment on the drop-jump test, and lower limb symmetry during single-leg hop tests [34]. The study involved 916 female and 224 male athletes who were involved in soccer, basketball, volleyball, baseball, football, and track and field. Extension peak torques significantly increased with age; maximum strength was noted in females at age 13 and in males at age 14 ($P < 0.001$, Fig. 17.44). Although maximum flexion strength occurred in males at age 14 ($P < 0.001$), females had only slight increases from ages 9–11 (Fig. 17.45). Males aged 14–17 years had significantly greater normalized isokinetic strength than age-matched females. No age or gender effects existed in limb alignment on the drop-jump test (Fig. 17.46) or limb symmetry on single-leg hop testing. The conclusions reached were that maximum hamstrings strength was noted in female athletes by age 11, compared to age 14 in males, and a distinct lower limb valgus alignment existed in the majority of all athletes on landing.

We examined age- and gender-associated development of isokinetic tibial internal rotation (IR) and external rotation (ER) strength in 94 athletes (47 females and 47 males) aged 11–17 years [35]. The study involved the measurement of IR and ER peak torque and time to peak torque at 120°/s and 180°/s and knee extension and flexion peak torque at 180°/s. IR and ER were tested with the subjects in a partial supine position with the hip flexed 60° and the knee flexed 90°. The results revealed that males 14–17 years of age had significantly greater mean IR, ER, flexion, and extension peak torques than males aged 11–13 years. No such age-related effect existed in females. There was no difference between genders aged 11–13 years in isokinetic strength. Males aged 14–17 years had on average 17% greater IR strength, 28% faster time to reach IR peak torque, 17% greater extension strength, and 20% greater knee flexion strength than age-matched females even after controlling for body mass index (Fig. 17.47).

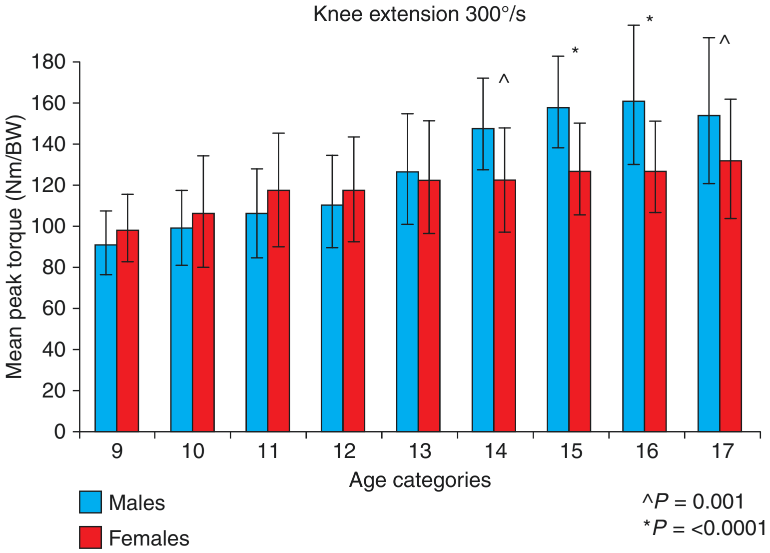

Fig. 17.44 No significant difference was found in the mean extensor peak torque ratio values between females and males in the 9- to 13-year-old age groups. However, from the ages of 14–17, males had significantly greater mean extensor peak torque ratio values than females (From Barber-Westin SD, Noyes FR, Galloway M: Jump-land characteristics and muscle strength development in young athletes: A gender comparison of 1140 athletes 9–17 years of age. Am J Sports Med 34: 375–384, 2006)

Fig. 17.45 No significant difference was found in the mean flexor peak torque ratio values between females and males in the 9–13-year old age groups. However, from the ages of 14–17, males had significantly greater mean flexor peak torque ratio values than females (From Barber-Westin SD, Noyes FR, Galloway M: Jump-land characteristics and muscle strength development in young athletes: A gender comparison of 1140 athletes 9–17 years of age. Am J Sports Med 34: 375–384, 2006)

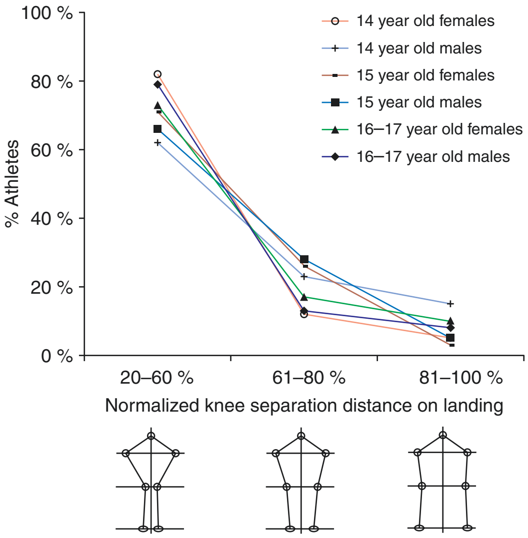

Fig. 17.46 There was no significant difference between either the male or female athletes aged 14–17 in the percent of subjects with <60%, 61–80%, or >80% normalized knee separation distance. The stick figures are representative of the knee separation distance, but not of the ankle separation distance (From Barber-Westin SD, Noyes FR, Galloway M: Jump-land characteristics and muscle strength development in young athletes: A gender comparison of 1140 athletes 9–17 years of age. Am J Sports Med 34: 375–384, 2006)

Critical Points

- Sportsmetrics significantly reduced noncontact ACL injury rates in female athletes.
- Sportsmetrics was effective in inducing changes in neuromuscular indices in female athletes.
  - Reduced deleterious abduction and adduction moments, lowered peak landing forces
  - Increased isokinetic knee flexor strength, improved hamstrings/quadriceps ratio
  - Improved overall lower limb alignment in the coronal plane on a drop-jump test
- Prepubescent athletes: no difference between genders.
  - Overall lower limb alignment on the drop-jump test
  - Lower limb symmetry on single-leg hop tests
  - Lower limb isokinetic muscle strength
- Athletes 9–17 years old: age and gender effects.
  - Extension peak torque increased with age; maximum strength was noted in females at age 13 and in males at age 14.

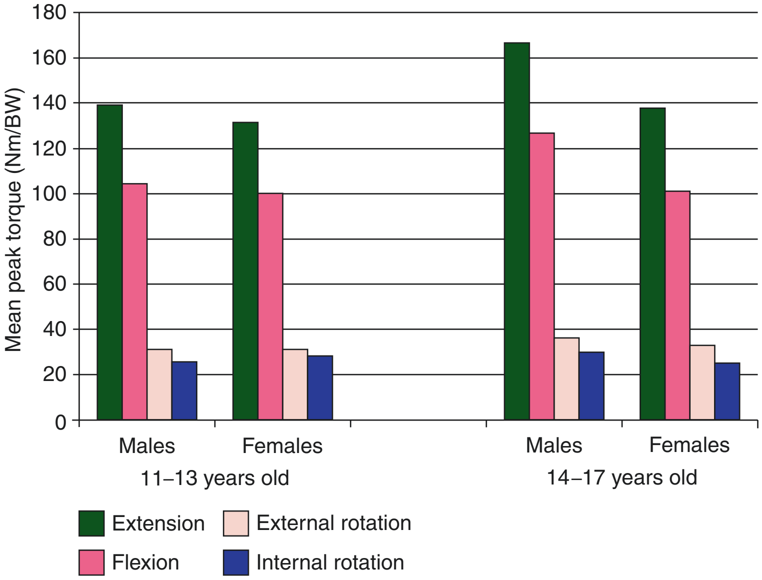

Fig. 17.47 Overall isokinetic peak torque averages for knee extensor, flexor, external rotation, and internal rotation for the dominant limb at 180°/s. A hierarchy of isokinetic muscle strength about the knee can be seen, which is similar between genders and age groups (From Noyes FR, Barber-Westin SD: Isokinetic profile and differences in tibial rotation strength between males and female athletes 11 to 17 years of age. Isok and Exer Sci 13: 251–259, 2005)

- Flexion peak torque increased with age in males, not in females.
- Extension and flexion peak torque: males 14–17 years old significantly greater strength than age-matched females.
- No age or gender effects in limb alignment on the drop-jump test, limb symmetry on single-leg hop testing.

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18

Sports-Specific Programs for Soccer, Basketball, Volleyball, and Tennis

Sue Barber-Westin and Frank R. Noyes

Abstract

This chapter describes several sports-specific programs in detail that implement the components of Sportsmetrics considered essential for knee ligament injury prevention and include other exercises and drills designed to improve dynamic balance, agility, speed, strength, and aerobic conditioning. The programs were developed to improve athlete, coach, and parental interest in ACL intervention training and athlete compliance with the exercise program. The agility, reaction, acceleration, speed, and endurance exercises and drills are illustrated and described in detail for soccer, basketball, volleyball, and tennis. The results of the programs' effectiveness on improving neuromuscular indices and athletic performance indicators are provided.

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18.1 Introduction

One common problem with the implementation of sports injury prevention training is that many athletes, parents, and coaches are only interested in performance enhancement programs. In addition, coaches typically do not want to take time away from practices, either preseason or during the season, solely for an injury prevention program. Problems with compliance of injury intervention training are well documented and have been discussed in detail in Chaps. 20 and 21. Therefore, we devised several sports-specific programs that implemented the components of Sportsmetrics considered essential for knee ligament injury prevention and included other exercises and drills designed to improve dynamic balance, agility, speed, strength, and aerobic conditioning [1–5]. The programs offer a unique blend of neuromuscular retraining and sports-specific enhancement tasks to both improve player skill and aerobic fitness and decrease the risk of a knee ligament injury. The ability to demonstrate that these programs are effective in improving certain components of athletic performance is important from both a research and marketing standpoint. To date, athletic performance indices have been studied in the Sportsmetrics Basketball [4], Sportsmetrics Volleyball [3], Sportsmetrics Soccer [5], and Sportsmetrics Tennis [1] programs.

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All sports-specific neuromuscular and performance programs begin with a 10-min dynamic warm-up to prepare the body for the physical demands of the sport 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. 17. The programs then move to sports-specific agility, speed, and aerobic conditioning drills described below. Strength and static flexibility exercises are then performed as described in Chap. 17.

18.1.1 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 [6, 7]. 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. Studies have shown that female athletes have different muscle activation patterns compared with males during various cutting maneuvers, such as an earlier onset of vastus lateralis activity and a longer duration of rectus femoris activity [8–13]. During unanticipated cutting maneuvers, women have greater knee abduction, hip external rotation, and ankle pronation compared with men [8, 12, 14]. During side cutting, women have reduced knee and hip flexion angles and increased peak knee valgus and ankle pronation angles compared with men [15, 16]. These findings may partially explain the gender disparity in ACL noncontact injuries that occur during cutting and pivoting [8].

ACL injury prevention training programs should include instruction to avoid these at-risk situations during landing from a jump, decelerating, cutting, and pivoting maneuvers [17, 18]. 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 most effective and efficient ways to achieve complex motor learning that will reduce the likelihood of a noncontact ACL injury continue to be investigated [19, 20]. However, 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 [20–22]. It has been postulated that athletes who are able to watch and critique their own performance in terms of technique may have an enhanced learning experience [19]. The use of implicit learning strategies that involve imitating what one observes, thereby decreasing the amount of cognitive understanding, may be potentially beneficial for injury prevention [19].

Recommended instructions for agility and reaction drills include the following (Fig. 18.1: [6, 18, 23–26].

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.

Fig. 18.1 (**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

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 [27].
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.

Critical Points

- Sports-specific programs designed using:
  - Components of Sportsmetrics essential for knee ligament injury prevention
  - Other exercises and drills to improve dynamic balance, agility, speed, strength, and aerobic conditioning
- Goal is to offer both injury prevention and performance enhancement to increase interest in training and improve compliance.
- All programs include dynamic warm-up, plyometrics, strength, and flexibility exercises from original Sportsmetrics program.
- Training includes proper instruction and techniques for deceleration, cutting, and pivoting.

18.2 Soccer (Table 18.1)

18.2.1 Agility and Reaction Drills

18.2.1.1 Serpentine Run

Arrange six cones in a zigzag pattern within a 15 × 37 ft. (4.6 × 11.3 m) area (Fig. 18.2). 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 and 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.

Table 18.1 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	Modified shuttle	¼ field, 3 reps
	4–6	Sprint-stop feet-listen	30 s, 2 reps
	7–9	Square drill	30′ × 30′ (9.1 m × 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 m × 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 yd (45.7 m), 5 reps
	1–3	Jog	4 laps around field (1280 yd, 1170 m)
	4–6	Acceleration with band	go to 10-yd (9.1 m) line
	4–6	Sprint with ground touches-backpedal	½ field or 50 yd (45.7 m), 5 reps
	4–6	100 yd (91.4 m) shuttle	3 × 100 (300 yd, 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 yd (45.7 m), 6 reps
	7–9	50 yd (45.7 m) shuttle	Up and back × 3 (300 yd, 274 m), 4 reps
	10–12	Acceleration with band	Go to 20-yd (18.3 m) line
	10–12	Box drill, sprint-90°-backpedal	½ field, 3 reps
	10–12	50-yd (45.7 m) cone drill: 10 yd (9.1 m)-back, 20 yd (18.3 m)-back, 30 yd (27.4 m)-back, 40 yd (36.6 m)-back, 50 yd (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 yd (45.7 m), 7 reps
	13–15	Jingle jangle, 20 yd (18.3 m)	Up and back × 5 (200 yd, 183 m), 5 reps
	16–18	Acceleration with band	Go to 30-yd (27.4 m) line
	16–18	Sprint-360°-sprint	½ field or 50 yd (45.7 m), 7 reps
	16–18	Jingle jangle, 10 yd (9.1 m)	Up and back × 5 (100 yd, 91 m), 6 reps

Table 18.1 (continued)

Component	Session no.	Exercise	Duration
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
Strength training	1–18	Resistance band: squats	30 s all exercises: sessions 1–6
		Resistance band: lunges	45 s all exercises: sessions 7–12
		Single-leg heel raise	60 s all exercises: sessions 13–18
		Prone hamstring with partner resistance	
		Supine hamstring bridge	
		Abdominals of choice	
		Hip flexion: resistance band knee drive with partner	
		Hip abductor: resistance band kicking with partner	
		Resistance band: arm swing	
		Wall sits	

[a] The dynamic warm-up, jump training, and static flexibility exercises are described in Chap. 17

18.2.1.2 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. 18.3). The athlete stands in the middle facing the 12 o'clock cone, which is the neutral position. The instructor calls out one of the four positions, and the 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.

18.2.1.3 Modified Shuttle Run

Arrange seven cones in a zigzag pattern within a 10 × 30 ft. (3.0 × 9.1 m) area (Fig. 18.4). 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 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. 18.4. Once the last cone is reached, the athlete sprints to midfield and then jogs back to the starting position.

18.2.1.4 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."

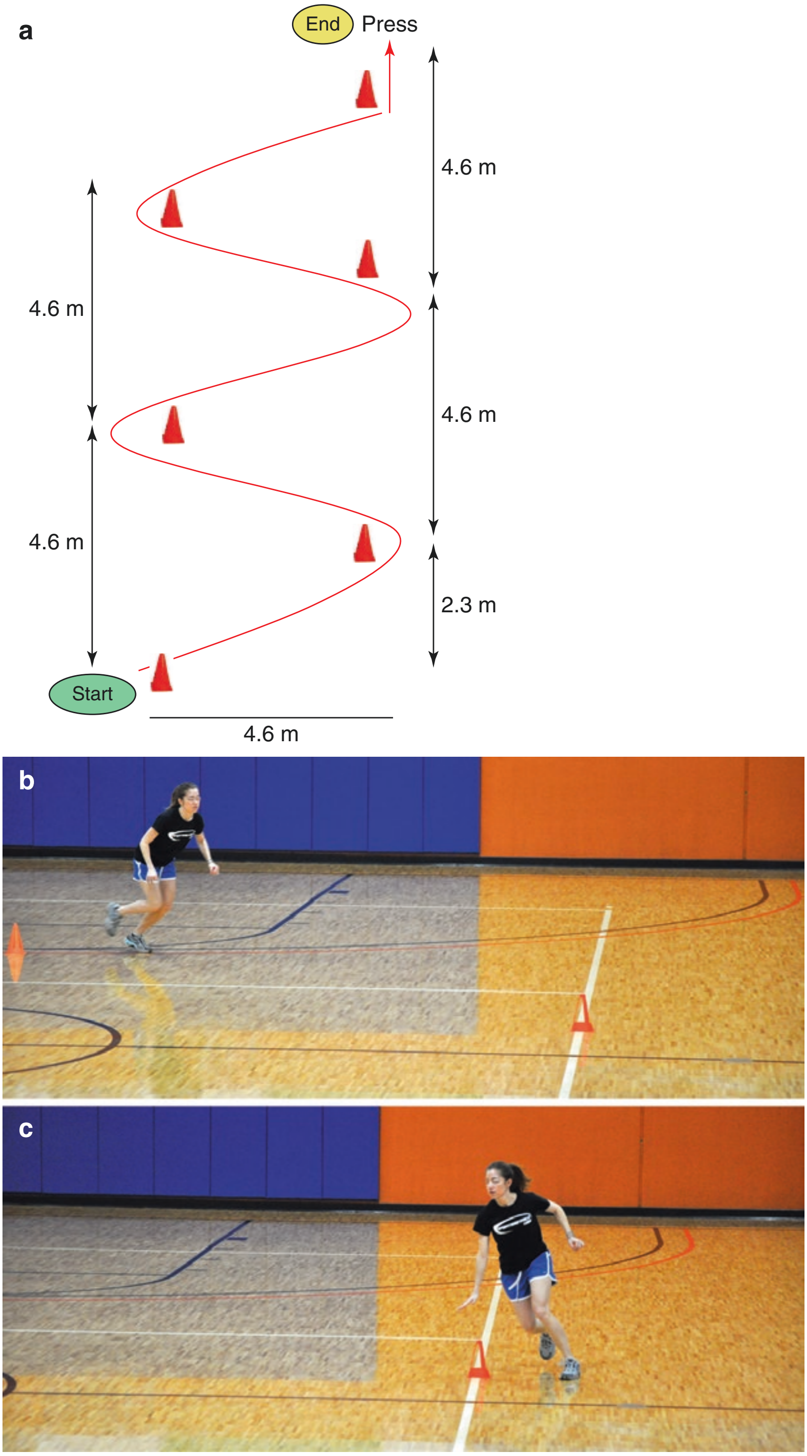


Fig. 18.2 Serpentine run: (**a**) course and (**b**, **c**) direction

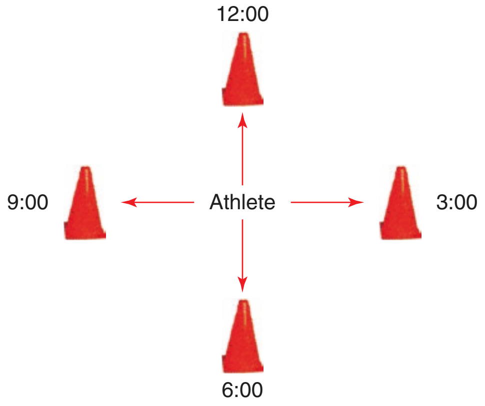


Fig. 18.3 Wheel drill

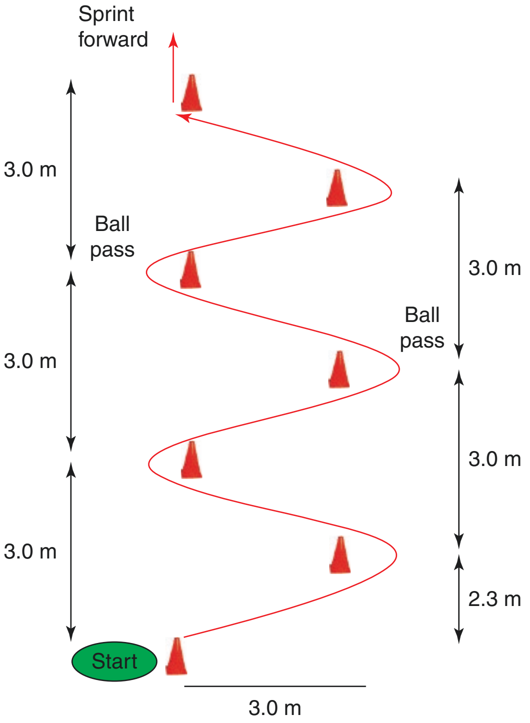


Fig. 18.4 Modified shuttle run

18.2.1.5 Square Drill

The athlete begins at the back corner of a 30 × 30 ft. square (9.1 × 9.1 m, Fig. 18.5). 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, 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.

18.2.1.6 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."

18.2.1.7 Nebraska Agility Drill

Arrange two cones 30 ft. (9.1 m) apart (Fig. 18.6). 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 reaching that cone, the athlete backpedals to the starting line.

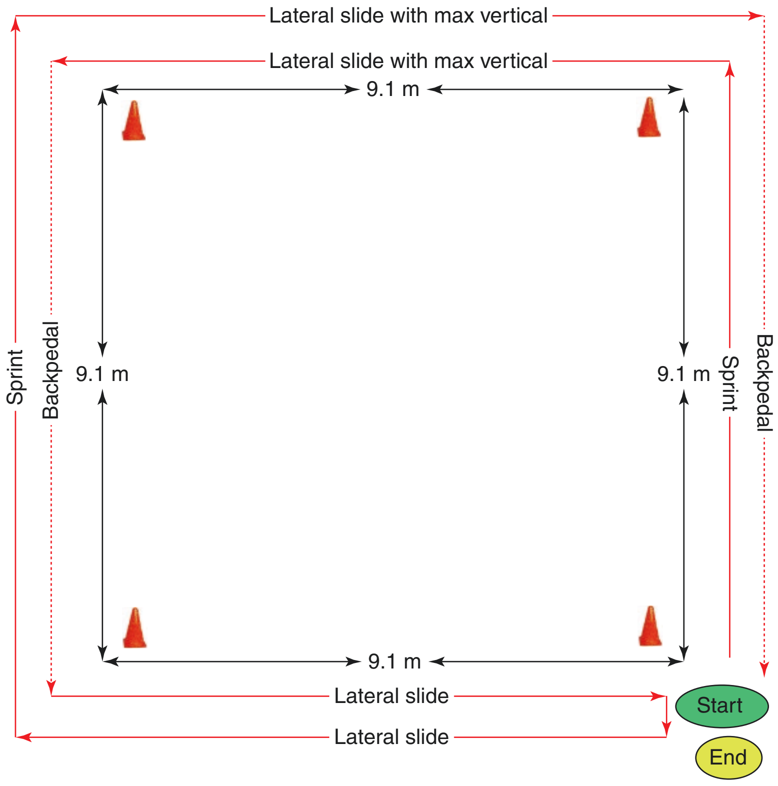
18.2.1.8 Reaction Drill-Watch Instructor Point

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.

18.2.1.9 Illinois Drill

Arrange four cones in a 30 × 30 ft. (9.1 × 9.1 m) square (Fig. 18.7). 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

Fig. 18.5 Square drill



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.

18.2.1.10 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.

18.2.1.11 T-Drill: 5-10-5

Arrange three cones and a start/finish marker so that they form the capital letter "T" (Fig. 18.8). 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 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.

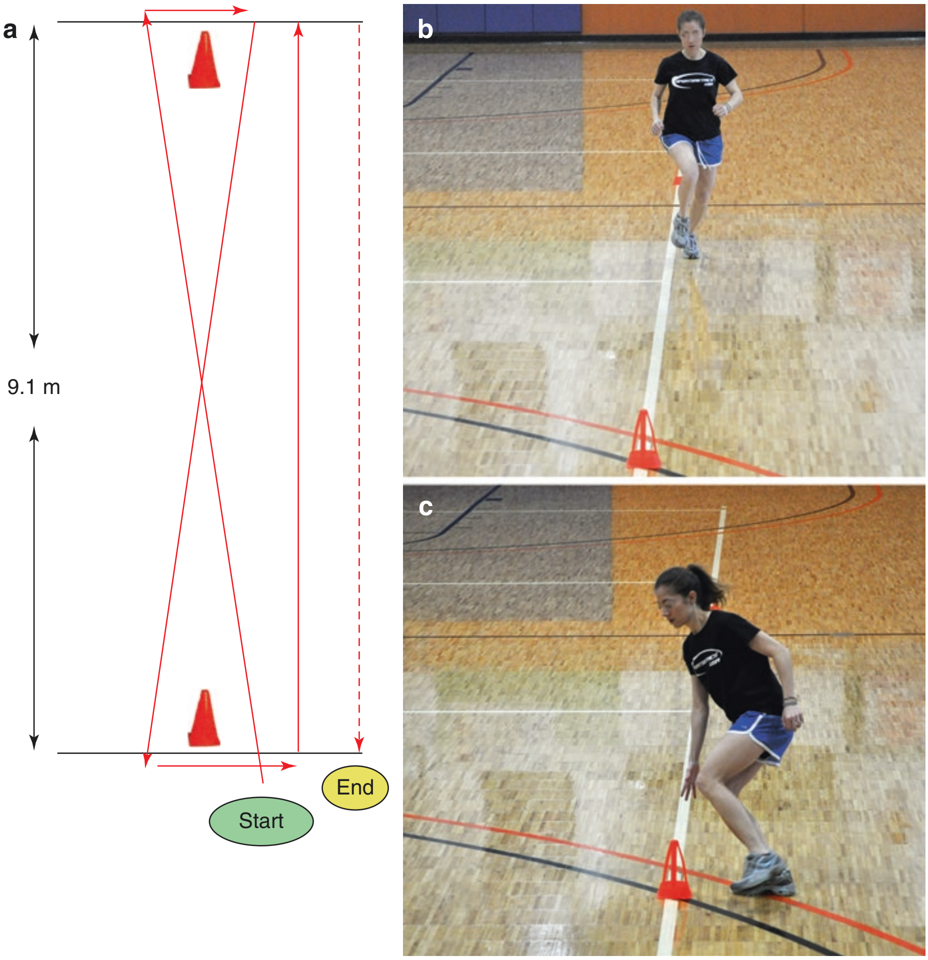


Fig. 18.6 Nebraska agility drill: (**a**) course and (**b**, **c**) direction. Solid lines indicate forward sprinting, dotted line indicates backpedalling

18.2.1.12 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 one of the four 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.

18.2.2 Acceleration, Speed, and Endurance Drills

18.2.2.1 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. 18.9). 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

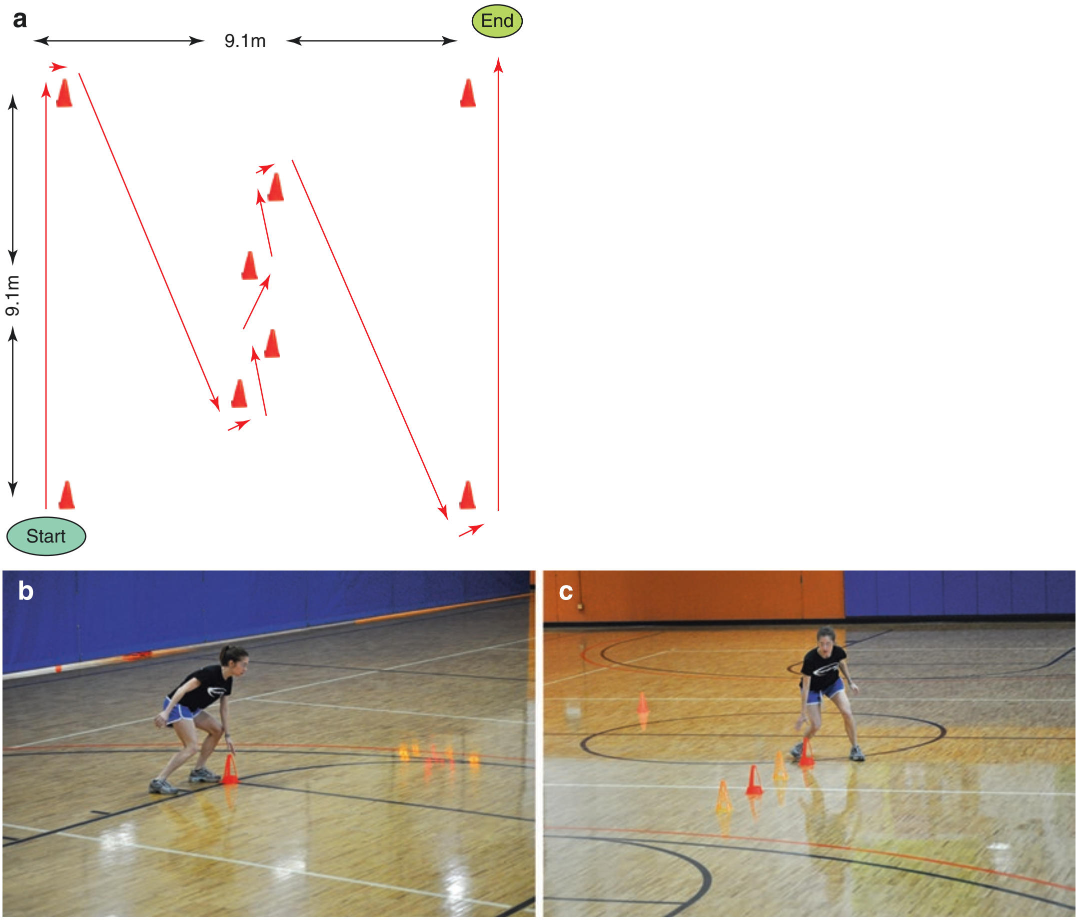


Fig. 18.7 Illinois drill: (**a**) course and (**b**, **c**) direction

them stationary 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 5–10 strides. Then, the partners switch rolls and complete the drill again.

18.2.2.2 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.

18.2.2.3 Sprint with Ground Touches-Backpedal

The athlete begins on the end line and sprints forward to a cone placed 15 yd (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 yd (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.

18.2.2.4 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.

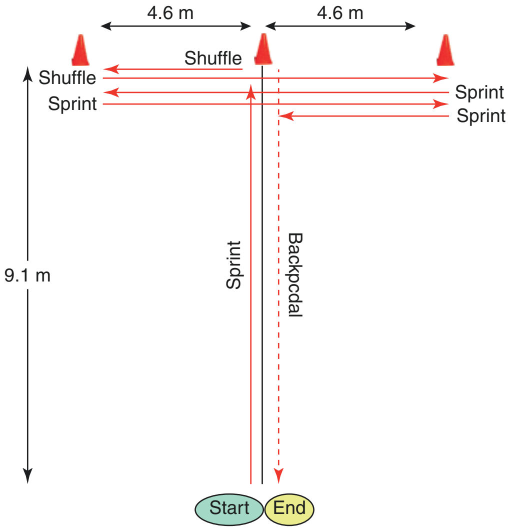


Fig. 18.8 T-drill. The shuffles and sprints at the top of the "T" are done in a straight line. The figure depicts the five segments individually for illustrative purposes only

18.2.2.5 Box Drill, Sprint-90°-Backpedal

The athlete begins at the bottom right corner of the penalty box (Fig. 18.10). Upon command, they sprint forward to the top of the box and perform a 90° turn by pivoting on the left foot and

Fig. 18.9 Partner push-offs

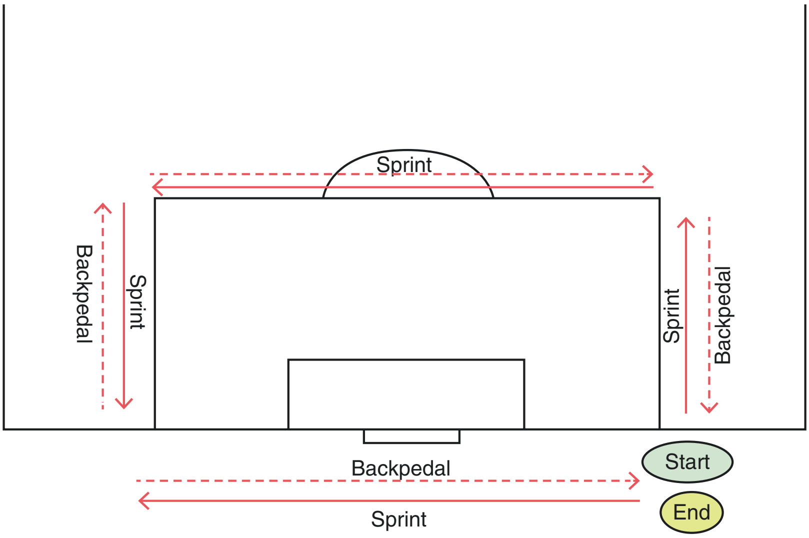


Fig. 18.10 Box drill, sprint-90°-backpedal

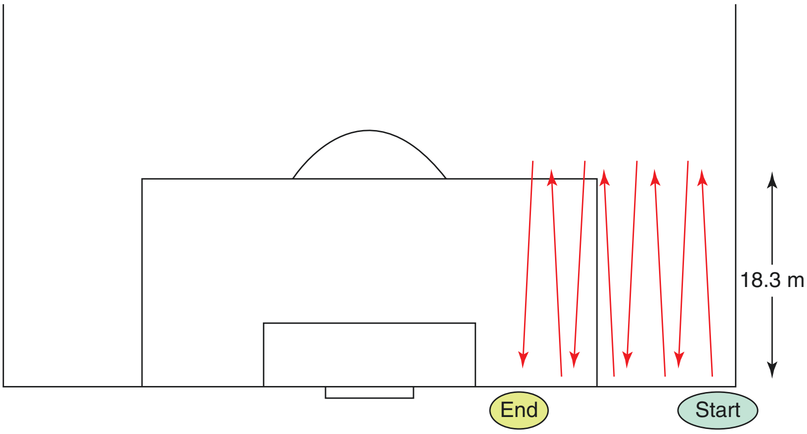


Fig. 18.11 Jingle jangle drill

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.

18.2.2.6 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 penalty line, the athlete completes another 180° turn and backpedals to the starting position.

18.2.2.7 Jingle Jangle

The athlete sprints a series of five repetitions of 20 yd (18.3 m), up and back (Fig. 18.11).

18.2.2.8 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.

18.2.3 Ladders, Quick Feet, and Additional Jump Drills

18.2.3.1 Ladder: Up-Up and Back-Back

A 15-ft (4.6 m) ladder is placed along the sideline (Fig. 18.12). 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.

18.2.3.2 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

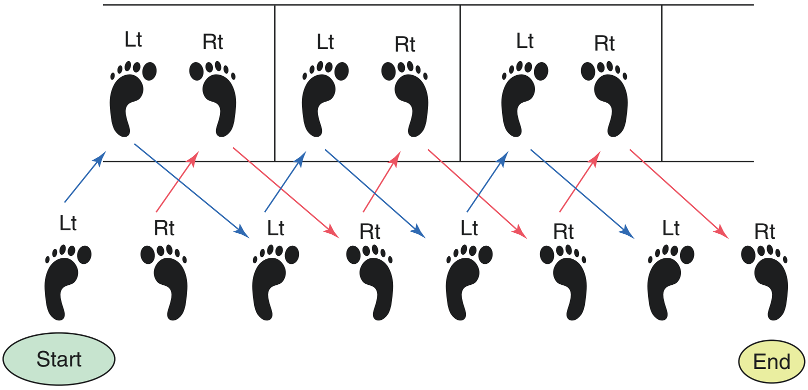


Fig. 18.12 Ladder: up-up and back-back. Only a portion of the 4.6 m ladder is shown for illustrative purposes

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.

18.2.3.3 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. 18.13). Then, the athlete steps the 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.

18.2.3.4 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. 18.14. 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 return to the starting position.

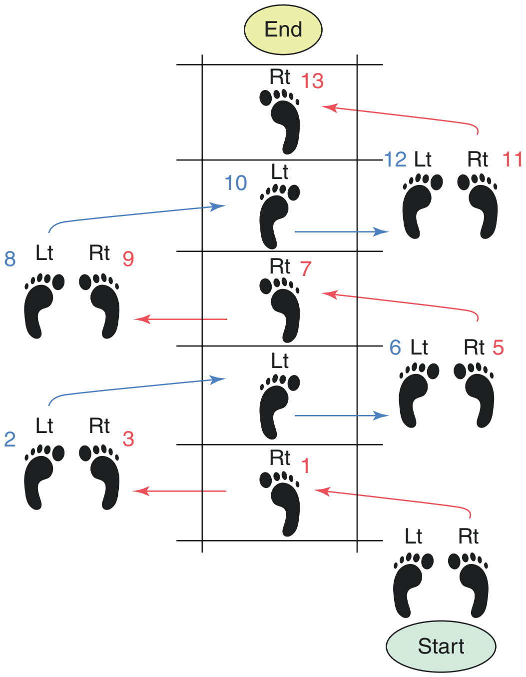


Fig. 18.13 Ladder: outside foot in. Only a portion of the 4.6 m ladder is shown for illustrative purposes

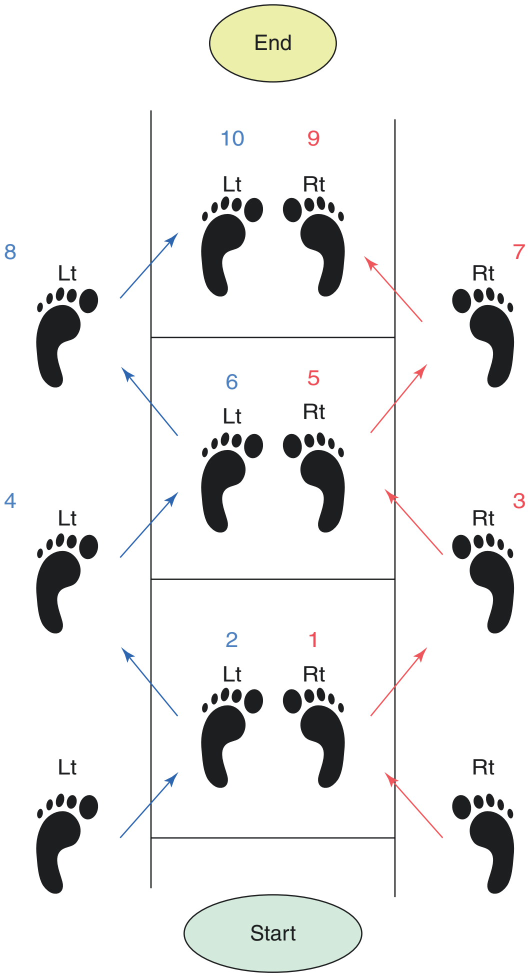


Fig. 18.14 Ladder: in-in, out-out. Only a portion of the 4.6 m ladder is shown for illustrative purposes

18.2.3.5 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. 18.15). 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, 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.

18.2.3.6 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. 18.16. The athlete jumps to B, then continues to C, D, E, C, and back to A.

18.2.3.7 Dot Drill: Split-Leg Jumps

The athlete performs the double-leg jump pattern, ending with both feet on C shown in Fig. 18.17. 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.

18.2.3.8 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. 18.18. 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.

18.2.3.9 Dot Drill: Single-Leg Hops

The athlete performs the180° 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. 18.19). 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 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.

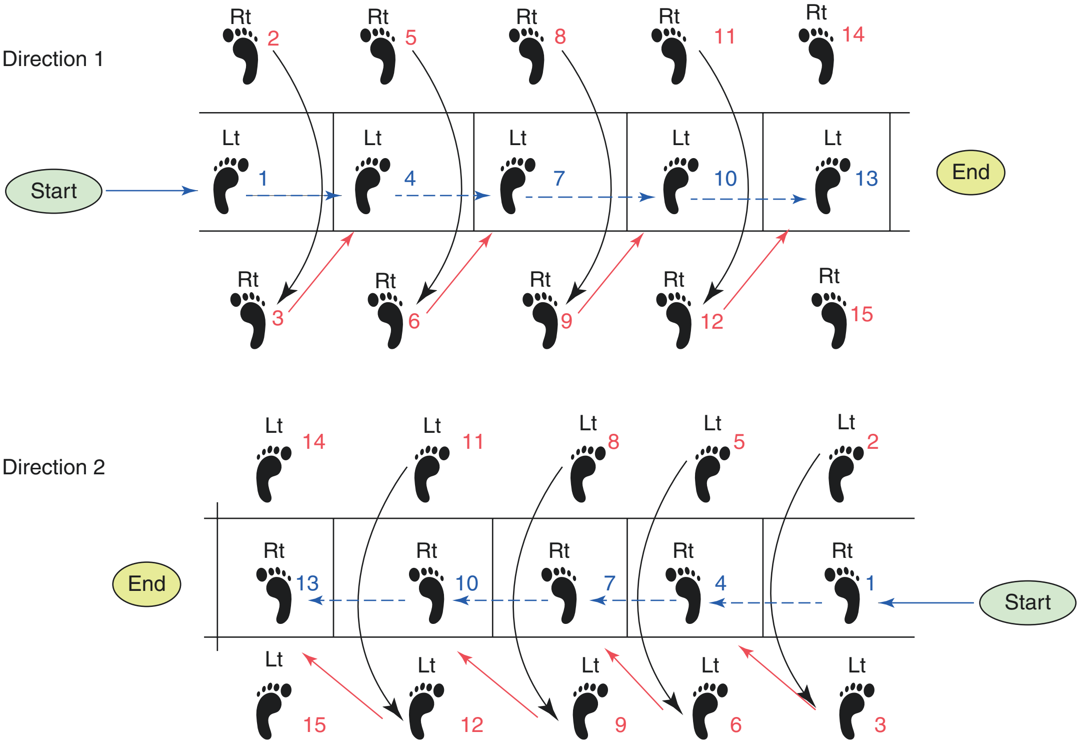


Fig. 18.15 Ladder: 1 foot forward, 1 foot backward. Only a portion of the 4.6 m ladder is shown for illustrative purposes

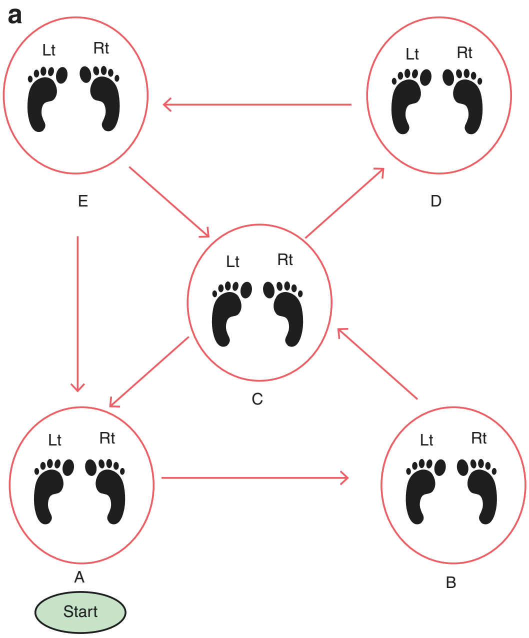


Fig. 18.16 Dot drills: double-leg jumps; (**a**) patterns and (**b–d**) directions

18.2.3.10 Dot Drill: Combo All Jumps

Perform all four patterns as described above.

18.3 Basketball (Table 18.2)

18.3.1 Agility and Reaction Drills

18.3.1.1 Shuttle Drill

A course is set with six cones in a zigzag pattern within a 15 × 30 ft. (4.6 m × 27.4 m) area as shown in Fig. 18.20. Beginning at the first cone, the athlete sprints diagonally toward the second cone. Upon approaching the second cone, the athlete decelerates to allow for a defensive close-out. 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

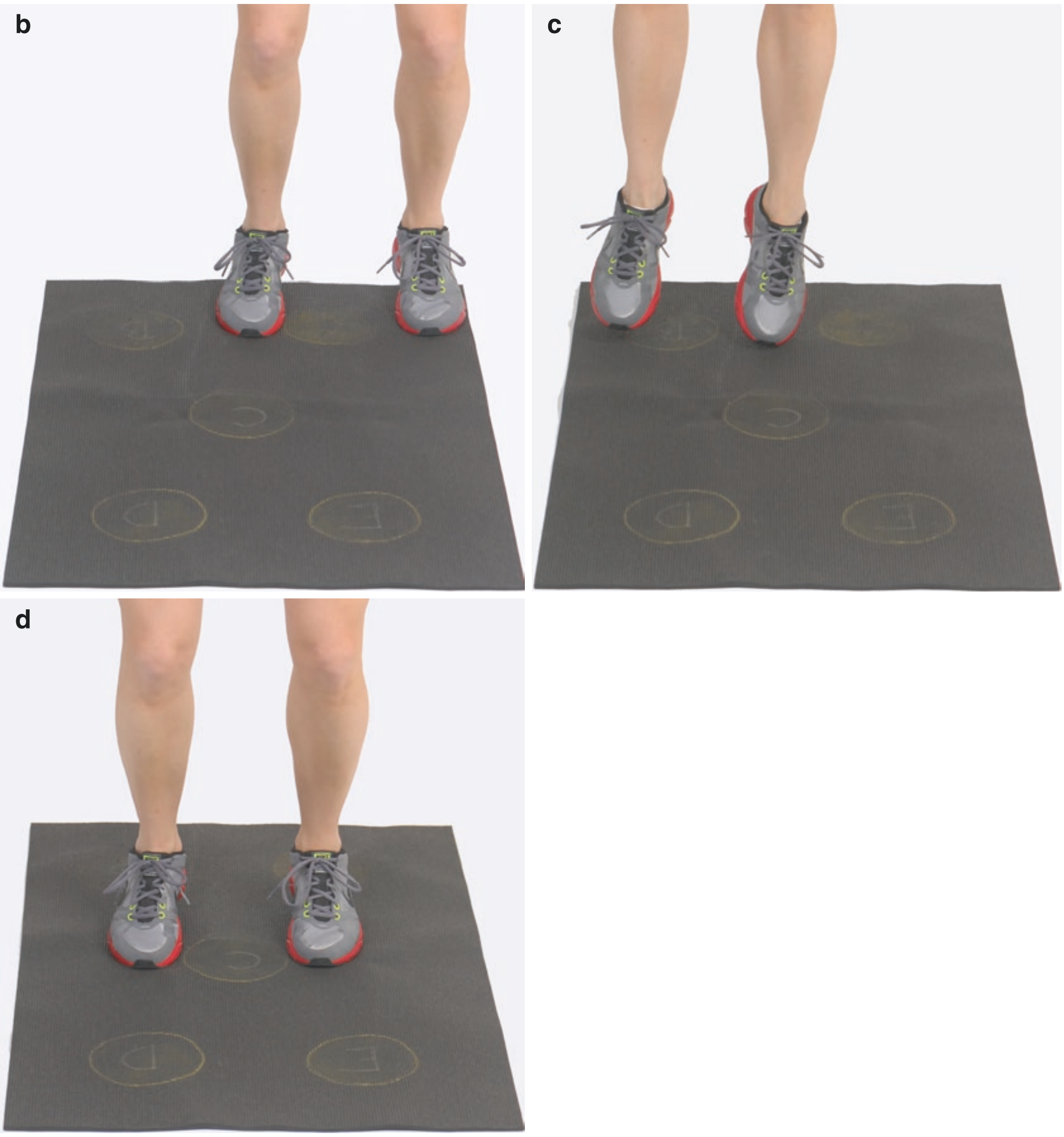


Fig. 18.16 (continued)

sprints to the sixth cone where a 90° transition is done. The athlete then backpedals until the sideline is reached.

18.3.1.2 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. 18.21. 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.

18.3.1.3 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.

18.3.1.4 Figure 4 Drill

Four cones are arranged as shown in Fig. 18.22. 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 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.

18.3.1.5 Square Drill

The athlete begins at the back corner of a large square as shown in Fig. 18.5. 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

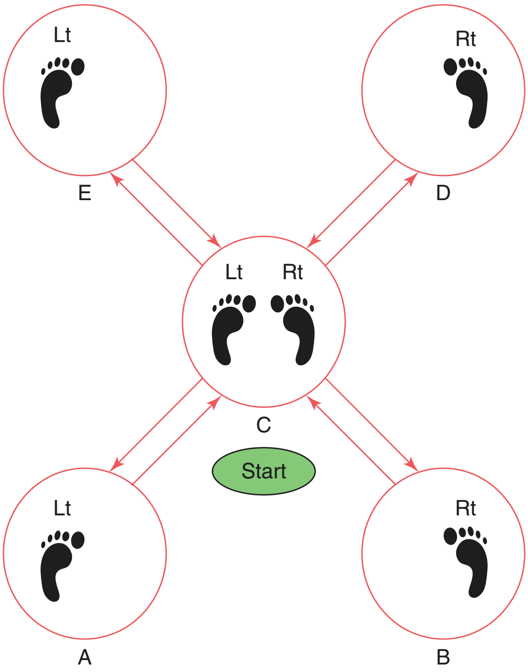


Fig. 18.17 Dot drills: split-leg jumps

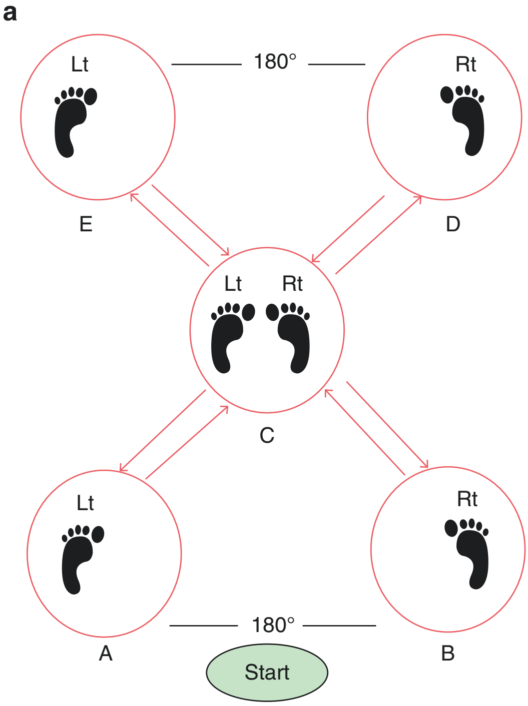


Fig. 18.18 Dot drills: 180° split-leg jumps; (**a**) patterns and (**b**–**d**) directions

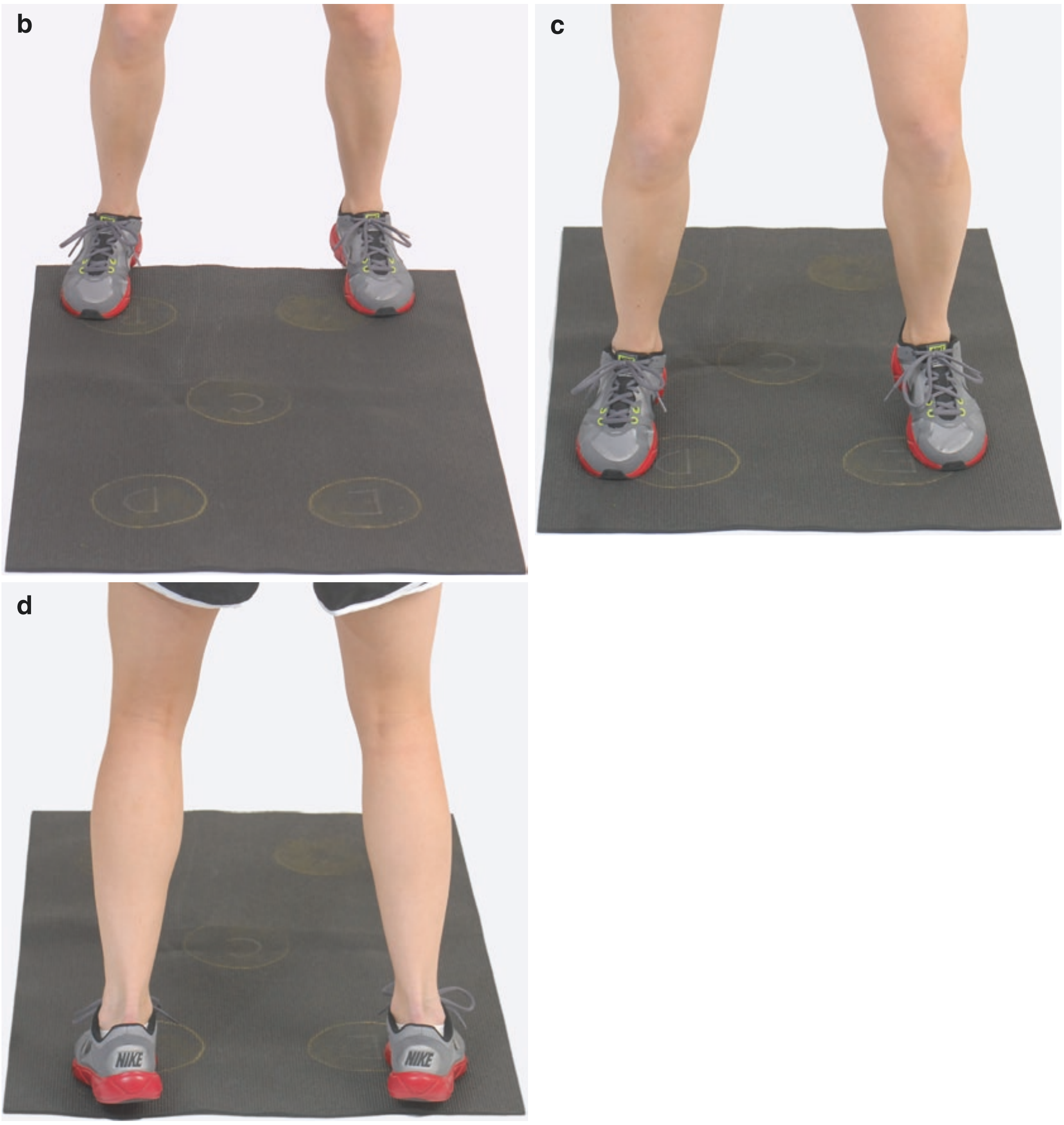


Fig. 18.18 (continued)

ball is passed to the athlete for a quick shot or a pass back to the instructor.

18.3.1.6 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. 18.23. 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 yd (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 three-point line. At this point, the instructor passes a ball to the athlete where they

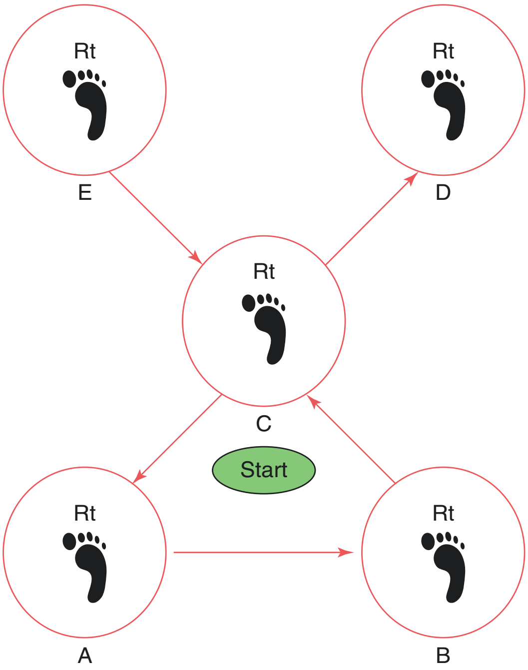


Fig. 18.19 Dot drills: single-leg hops

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.

18.3.1.7 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.

18.3.1.8 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. 18.24). 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.

18.3.1.9 Irish D Drill

The athlete begins at the baseline, underneath the basket (Fig. 18.25), and performs five power jumps. The athlete then moves using defensive slides along the baseline to the three-point line. They sprint from the three-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 then repeat the defensive slide/sprint pattern on the opposite side to complete one repetition.

18.3.1.10 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. 18.8. 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.

18.3.1.11 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

Table 18.2 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-drills: 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
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

Table 18.2 (continued)

Component	Session No.	Exercise	Duration
Strength training, on the court	1–18	Squats with resistance band	30 s all exercises: sessions 1–6
		Lunges with resistance band	45 s all exercises: sessions 7–12
		Single-leg heel raises	60 s all exercises: sessions 13–18
		Prone hamstring: hip extension with knee flexion	Lower extremity done on Monday and Friday
		Supine hamstring bridge	Upper extremity done on Wednesday
		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] The dynamic warm-up, jump training, and flexibility exercises are described in Chap. 17

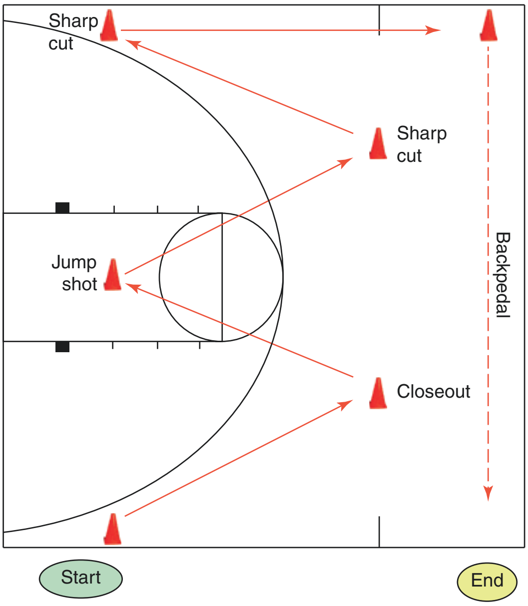


Fig. 18.20 Basketball shuttle drill. Solid red lines indicate forward sprints; dotted line indicates backpedaling

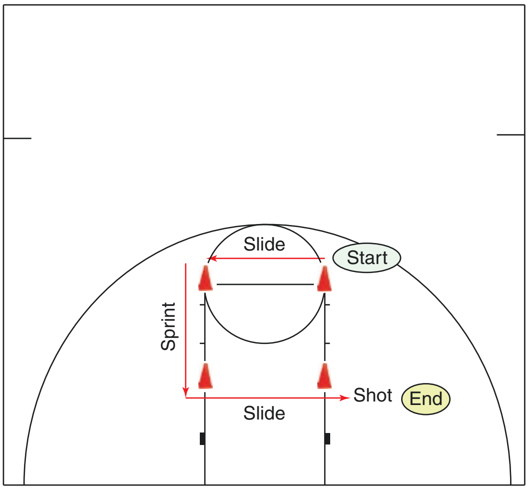


Fig. 18.21 Maze drill

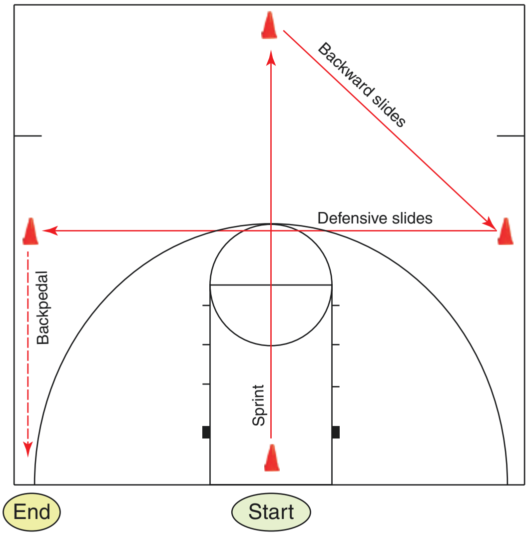


Fig. 18.22 Figure 4 drill

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 knockout 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.

18.3.2 Acceleration, Speed, and Endurance Drills

18.3.2.1 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. 18.26) Alternate to the opposite leg in a quick motion and continue 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.

18.3.2.2 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.

18.3.2.3 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. 18.27).

18.3.2.4 Suicides Forward-Backward

This is the same suicide drill as described above, except the athlete sprints forward and always return to the starting baseline by backpedaling.

18.3.2.5 ¼ Eagle Sprint-Backpedal

See section "¼ Eagle Sprint-Backpedal."

18.3.2.6 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.

18.3.2.7 Sprint with Ground Touches

The athlete begins on one baseline and sprints forward. Cones are positioned 15 yd (13.7 m) and 30 yd (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.

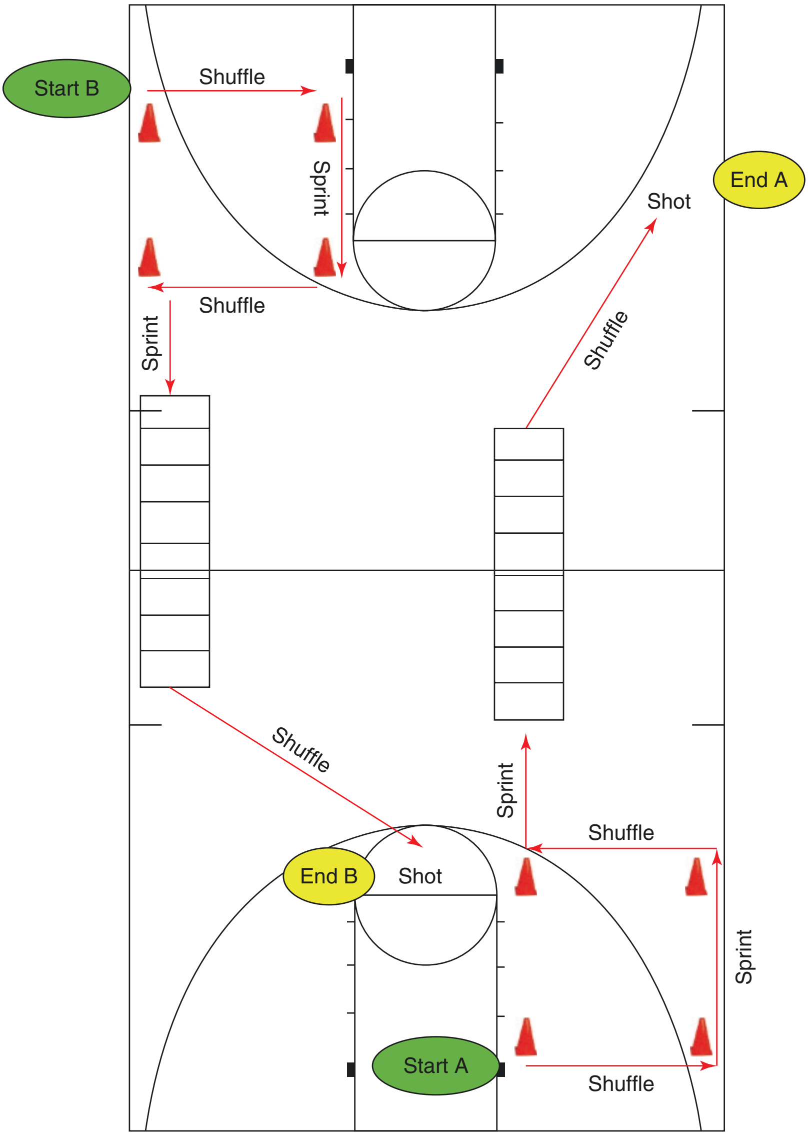


Fig. 18.23 4 dot drill, ladder

18.3.2.8 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.

18.3.2.9 Sprint-180°-Backpedal

See section "Sprint-180°-Backpedal."

18.3.2.10 Sprint-Quick Feet-Backpedal

The players begin at the end line and sprint until the instructor commands "stop," at which time the

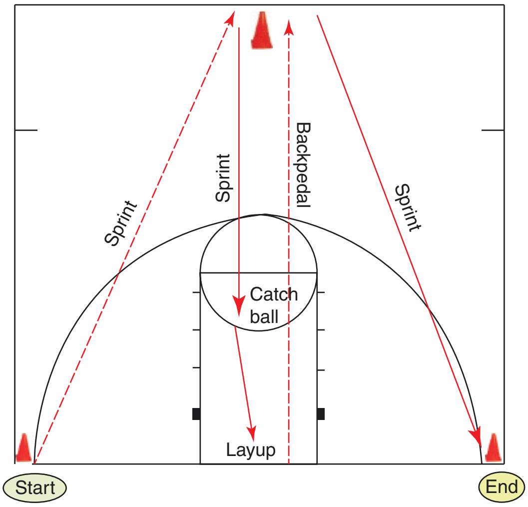


Fig. 18.24 Shoot and sprint drill

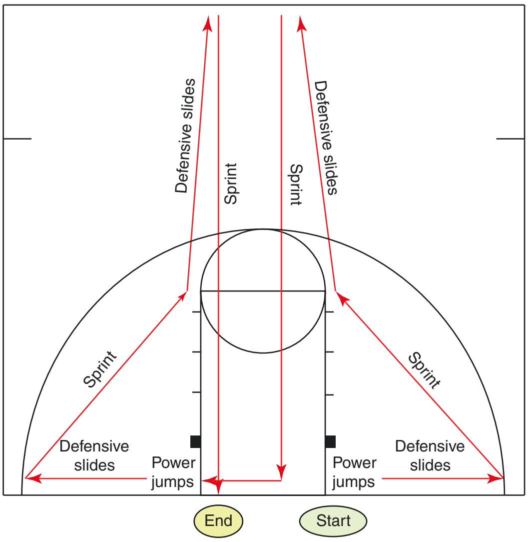


Fig. 18.25 Irish D drill

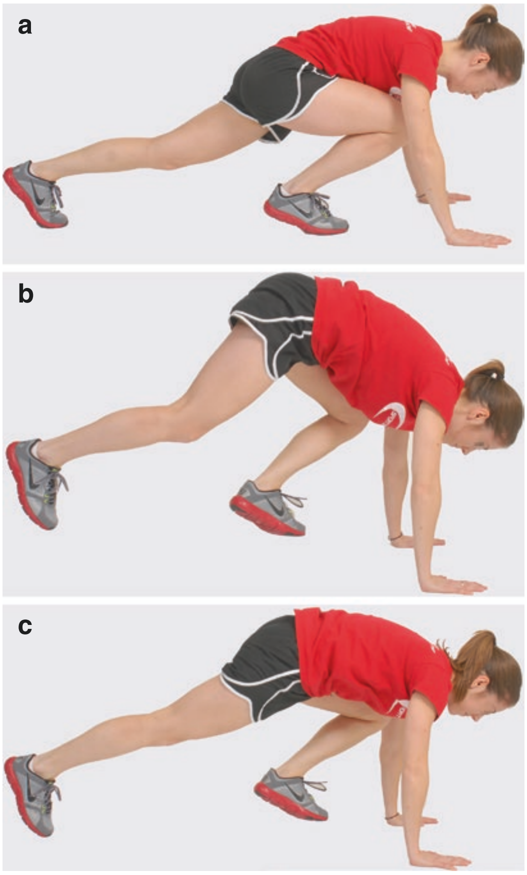


Fig. 18.26 Mountain climbers: (**a**) starting position, (**b**) leg switch, and (**c**) return to starting position

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.

18.3.2.11 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.

18.3.2.12 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. 18.28). 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 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

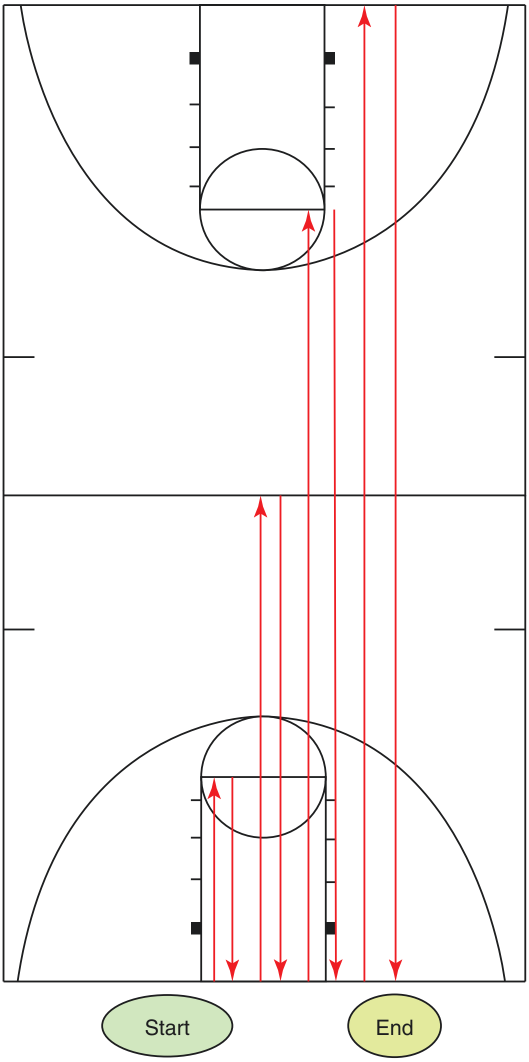


Fig. 18.27 Suicides on a basketball court. Run is done in a straight line; the figure depicts the eight segments individually for illustrative purposes only

signal for the next teammate to begin; the winner is the first team to have all of their members cross the opposite baseline.

18.3.3 Ladders, Quick Feet, and Additional Jump Drills

18.3.3.1 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. 18.29). The entire length of the ladder is traveled, and then the athlete immediately sprints forward (10–20 yd, 9.1–18.3 m) and jogs back to the starting position.

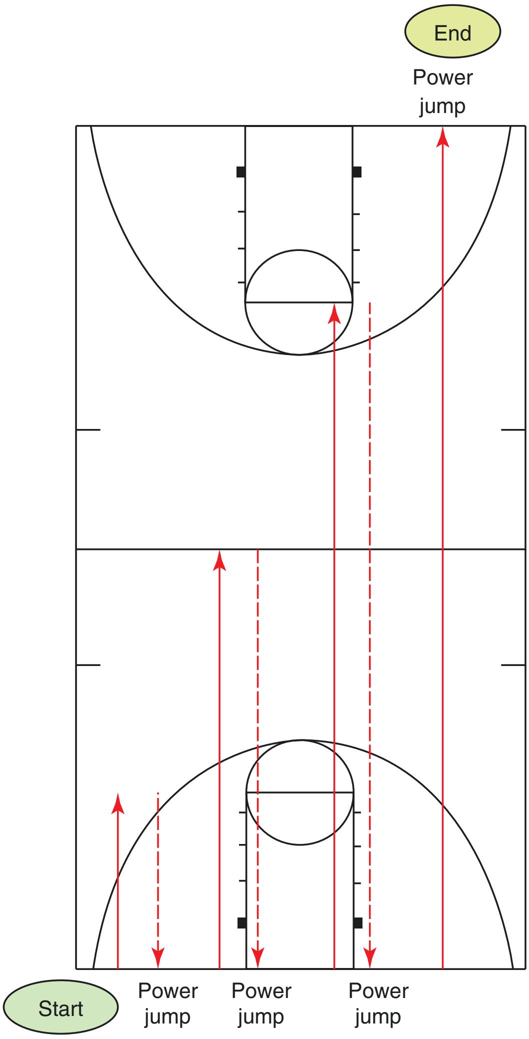


Fig. 18.28 Power rebounds relay. Solid lines indicate forward sprints; dotted lines indicate backpedaling

18.3.3.2 Ladder: Up-Up/Back-Back

See section "Ladder: Up-Up/Back-Back."

18.3.3.3 Ladder: Outside Foot In

See section "Ladder: Outside Foot In."

Fig. 18.29 Ladder: high knees from the (**a**) front and (**b**) side positions

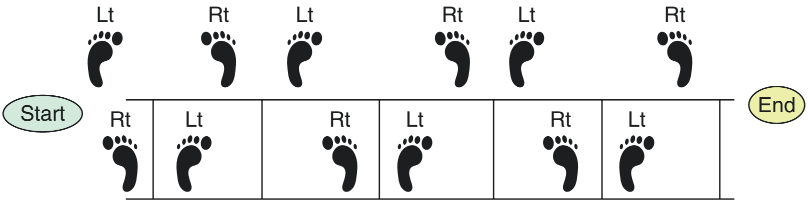


Fig. 18.30 Ladder: scissors. Only a portion of the ladder is shown for illustrative purposes

18.3.3.4 Ladder: In-In, Out-Out

See section "Ladder: In-In, Out-Out."

18.3.3.5 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. 18.30). The athlete jumps up in the air, both feet leaving the ground at the same time, and scissors 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.

18.3.3.6 Ladder: Icky Shuffle

The athlete begins by stepping the right foot in the first box, followed by the left foot (Fig. 18.31). 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.

18.3.3.7 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 the chest in a "Heisman" position (Fig. 18.32). 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 the 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.

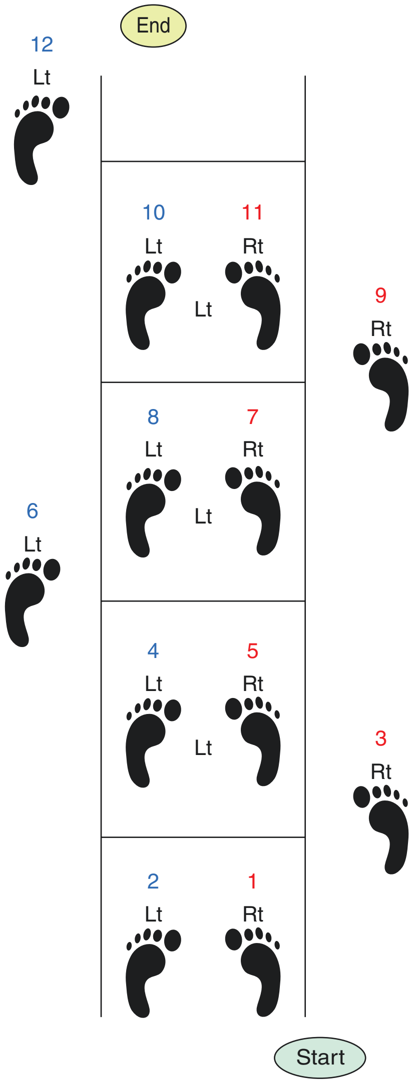


Fig. 18.31 Ladder: Icky shuffle. Only a portion of the ladder is shown for illustrative purposes

18.3.3.8 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.

18.3.3.9 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.

18.3.3.10 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.

18.3.3.11 180° Scissor Jumps

The 180° scissor jump is similar to the 180° jump described in Chap. 17. The athlete begins in a deep lunge position with the right foot forward.

Fig. 18.32 High knee ball toss over barrier, "Heisman" position: (**a**) starting position and (**b**) after hop over barrier catching ball

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.

18.3.3.12 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."

18.4 Volleyball (Table 18.3)

18.4.1 Agility and Reaction Drills

18.4.1.1 Volleyball Shuttle Drill

Arrange six cones in a zigzag pattern within a 15 × 30 ft. (4.6 × 9.1 m) area (Fig. 18.33). The athlete begins at the first cone and sprints diagonally to the second cone. Upon approaching the second cone, the athlete decelerates to allow for a block. As soon as the block is performed, the athlete immediately accelerates to the next cone, repeating a block every time a cone is reached. After reaching the fifth cone, the athlete accelerates to the sixth cone where they make a 90° transition and backpedal until the sideline is reached.

18.4.1.2 Volleyball Tip Drill

The team or players are divided in half and form a straight line facing each other 10 yd (9.1 m) apart. A player from one side begins the drill by setting the ball to the first player in the opposing line and then immediately runs to the end of the opposing line. The player receiving the ball sets the ball to the next player in the opposing line and immediately runs to the end of the opposing line.

Table 18.3 Sportsmetrics Volleyball training program[a]

Component	Session no.	Exercise	Duration
Agility, reaction	1–3	Volleyball shuttle	3 reps
	4–6	Volleyball tip drill	2 reps
	7–9	Square drill	3 reps
	10–12	Nebraska drill	4 reps
	13–15	Illinois drill	5 reps
	13–15	Shuffle pass with partner	1 set
	16–18	T-drill: 5-10-5	4 reps
	16–18	Shuffle set with partner	1 set
Acceleration, speed, endurance	1–3	Partner push-offs, hold 5 s	5 reps
	1–3	Sprint, backpedal	5 reps
	4–6	Acceleration sprint with band, hold 5 s	5 reps
	4–6	Sprint, backpedal	7 reps
	7–9	Mountain climbers	6 reps
	7–9	¼ Eagle into sprint-listen to instructor	6 reps
	10–12	Partner push-off, hold 5 s	6 reps
	10–12	Forward sprints with ground touches	5–7 reps
	13–15	Acceleration sprints with band	15 s, 5 reps
	13–15	Sprint-180°-backpedal	7 reps
	16–18	Mountain climbers	5–7 reps
	16–18	Sprint-360°-backpedal	5–7 reps
Ladders, quick feet, additional jumps	1–3	Ladder: high knees	4–6 reps
	1–3	Wheel drill-listen to instructor	30 s, 2 reps
	1–3	Suicide-volleyball court × 2	2 reps
	1–3	Dot drill: double-leg jumps	5 reps × 3
	4–6	Ladder: up-up/back-back	4–6 reps
	4–6	Sprint-stop feet-listen to instructor	30 s, 2 reps
	4–6	Suicides-forward/backward, volleyball court x 2	2 reps
	5–7	Dot drill: add split leg jumps	5 reps × 3
	7–9	Ladder: outside foot in	4–6 reps
	7–9	Sprint-quick feet-listen to instructor	30 s, 2 reps
	7–9	Suicides-lateral shuffle, volleyball court × 2	2 reps
	7–9	Dot drill: add 180° jumps	5 reps × 3
	10–12	Ladder: In-in/out-out	4–6 reps
	10–12	Reaction drill-watch instructor point	45 s, 2 reps
	10–12	Jingle jangle	10 yd (9.1 m) up-back, 4–6 reps
	10–12	Dot drill: add single-leg hops	5 reps × 3
	13–15	Ladder: scissors	4–6 reps
	13–15	Reaction mirror drill-partner pressing	45 s, 1 reps
	13–15	Jingle jangle	20 yd (18.3 m) up-back, 4–6 reps
	16–18	Ladder: Icky shuffle	4–6 reps
	16–18	Reaction instructor pointing + quick feet + up/down with push-up	45 s, 2 reps
	16–18	Power rebounds relay	1 set

(continued)

Table 18.3 (continued)

Component	Session no.	Exercise	Duration
Strength training, on the court	1–18	Squats with resistance band	30 s all exercises: sessions 1–6
		Power lunges (pulsating)	45 s all exercises: sessions 7–12
		Single-leg heel raises	60 s all exercises: sessions 13–18
		Supine hamstring bridge, single leg	
		Seated scapular retraction	
		Seated latissimus pull with resistance band	
		Seated scapular protraction with resistance band	
		Seated external rotation with resistance band	
		Partner internal rotation with resistance band	
		Abdominals of choice	
		Hip flexor resistance band kicking with partner	
		Steamboats (hip flexion)	
		Hip abductor resistance band kicking with partner	
		Lateral walking with resistance band	

[a] The dynamic warm-up, jump training, and flexibility exercises are described in Chap. 17

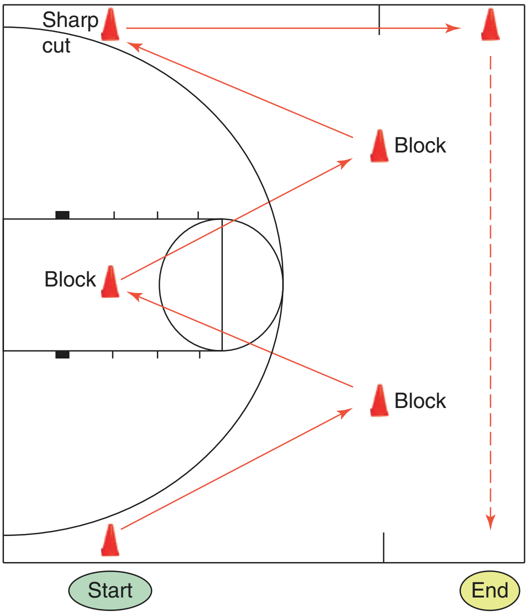


Fig. 18.33 Volleyball shuttle drill. Solid red lines indicate forward sprints; dotted line indicates backpedaling

This pattern is continually repeated as the athletes rotate through each line, trying to keep the ball in the air.

18.4.1.3 Square Drill

See section "Square Drill."

18.4.1.4 Nebraska Drill

See section "Nebraska Drill."

18.4.1.5 Shuffle Pass with Partner

Two athletes face each other and, upon command, shuffle back and forth between two cones. One athlete holds a ball, and every time a cone is reached, they toss the ball to their partner who then passes the ball back. This is repeated ten times down and back between the two cones, and then the athletes switch positions and repeat the drill.

18.4.1.6 T-Drill: 5-10-5

See section "T-Drill: 5-10-5."

18.4.1.7 Shuffle Set with Partner

This is the same drill as *Shuffle Pass with Partner*, except the athlete receiving the ball jumps up to set the ball back to their partner.

18.4.2 Acceleration, Speed, and Endurance Drills

18.4.2.1 Partner Push-Offs

See section "Partner Push-Offs."

18.4.2.2 Sprint-Backpedal

See section "Sprint-Backpedal."

18.4.2.3 Acceleration with Band

See section "Acceleration with Band."

18.4.2.4 Mountain Climbers

See section "Mountain Climbers."

18.4.2.5 ¼ Eagle into Sprint-Backpedal

See section "¼ Eagle into Sprint-Backpedal."

18.4.2.6 Sprints with Ground Touches

See section "Sprints with Ground Touches."

18.4.2.7 Sprint-180°-Backpedal

See section "Sprint-180°-Backpedal."

18.4.2.8 Sprint-360°-Backpedal

See section "Sprint-360°-Backpedal."

18.4.3 Ladders, Quick Feet, and Additional Jump Drills

18.4.3.1 Ladder: High Knees

See section "Ladder: High Knees."

18.4.3.2 Ladder: Up-Up/Back-Back

See section "Ladder: Up-Up/Back-Back."

18.4.3.3 Ladder: Outside Foot In

See section "Ladder: Outside Foot In."

18.4.3.4 Ladder: In-In/Out-Out

See section "Ladder: In-In/Out-Out."

18.4.3.5 Ladder: Scissors

See section "Ladder: Scissors."

18.4.3.6 Ladder: Icky Shuffle

See section "Ladder: Icky Shuffle."

18.4.3.7 Wheel Drill: Listen to Instructor

See section "Wheel Drill: Listen to Instructor."

18.4.3.8 Suicides-Volleyball Court × 2

Starting on the end line, the athlete sprints to the center line and back, to the far attack line and back, and to the far end line and back (Fig. 18.34). Immediately repeat the drill for one set.

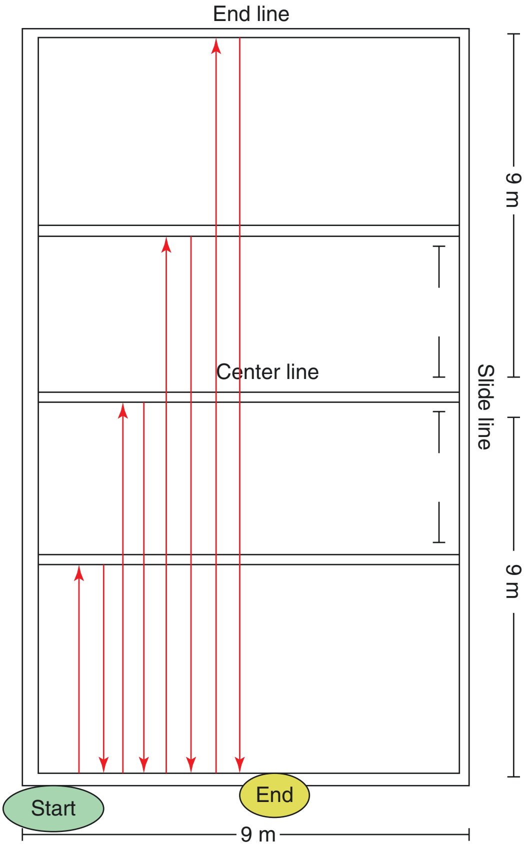


Fig. 18.34 Suicides on a volleyball court. Run is done in a straight line; the figure depicts the 8 segments individually for illustrative purposes only

18.4.3.9 Suicides-Forward/Backward, Volleyball Court × 2

This is the same suicide drill as described above, except the athlete sprints forward and always returns to the starting end line by backpedaling.

18.4.3.10 Suicides-Lateral Shuffle, Volleyball Court × 2

This is the same suicide drill as described above, except the athlete faces the sideline and shuffles through the entire pattern.

18.4.3.11 Sprint-Stop Feet-Listen to Instructor

See section "Sprint-Stop Feet-Listen to Instructor."

18.4.3.12 Sprint-Quick Feet-Listen to Instructor

See section "Sprint-Quick Feet-Listen to Instructor."

18.4.3.13 Reaction Drill-Watch Instructor Point

See section "Reaction Drill-Watch Instructor Point."

18.4.3.14 Jingle Jangle

See section "Jingle Jangle."

18.4.3.15 Reaction Mirror Drill-Partner Pressing

See section "Reaction Mirror Drill-Partner Pressing."

18.4.3.16 Reaction Instructor Pointing + Quick Feet + Up/Down with Push-up

This is the same drill as described in section "Reaction Drill-Watch Instructor Point" but with additional movements. During the drill, the instructor shouts the command "quick feet," and the athletes run with their feet in place until the next command "down" is given. At this time, the athletes drop to the ground and perform one push-up and immediately get back up to continue running in place until the next command is given.

18.4.3.17 Power Rebounds Relay

See section "Power Rebounds Relay."

18.4.3.18 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."

18.5 Tennis (Table 18.4)

18.5.1 Agility and Reaction Drills

18.5.1.1 Shadow Swing Baseline, Forehand and Backhand

The athlete starts 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

Table 18.4 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 ground stroke, 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

Table 18.4 (continued)

Component	Session no.	Exercise	Duration
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
Strength training, on the court	1–6	Medicine ball forehand & backhand	2 sets × 8 reps
	10–12	Medicine ball forehand and 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 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

[a] The dynamic warm-up, jump training, and flexibility exercises are described in Chap. 17

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. 18.35) 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, and 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.

Fig. 18.35 Shadow swing baseline, forehand and backhand. (**a**) starting position, (**b**) shoulder turn simulating forehand, and (**c**) completion of shoulder turn

18.5.1.2 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. 18.36). 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. 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

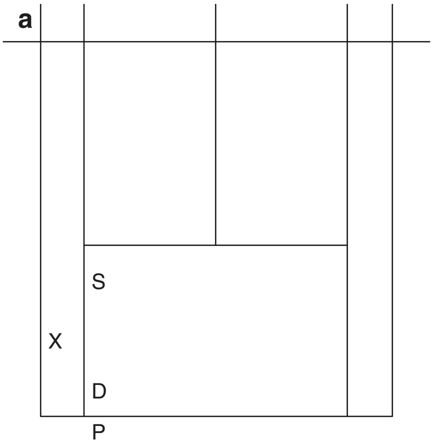


Fig. 18.36 Alternating short/deep balls forehand and backhand drill. *X* instructor; *P* player; *D* deep ball feed; *S* short ball feed. (**a**) diagram showing positions, (**b**) short forehand shot, and (**c**) turn to prepare for deep forehand

Fig. 18.36 (continued)

sideways for short balls and hit with an open stance.

18.5.1.3 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 ten consecutive balls are fed to the forehand. After a 30-s rest, the same drill is repeated to the backhand.

18.5.1.4 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 stable as possible, make small adjustments with the feet, and stay low.

18.5.1.5 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 8 shots are performed.

18.5.1.6 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.

18.5.1.7 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.

18.5.1.8 Up-Up, Back-Back, Sprint to Ground Stroke, Sprint to Volley, Forehand and Backhand

This drill incorporates the up-up, back-back ladder drill (see section "Ladder: Up-Up and Back-Back") with an additional ground stroke and volley. A ladder is positioned behind the baseline as shown in Fig. 18.37. The athlete proceeds through the ladder using the up-up, back-back pattern. 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. 18.37, 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.

18.5.2 Acceleration, Speed, and Endurance Drills

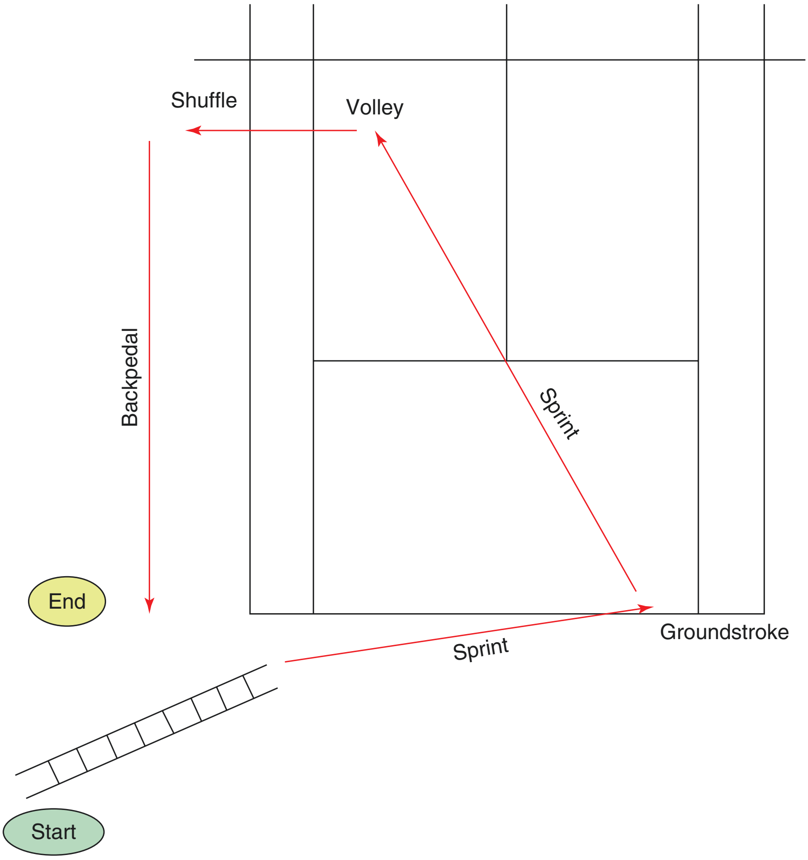
18.5.2.1 Suicides, 1 Court

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 (see Fig. 18.8). On clay courts, the athlete should be encouraged to slide into the ball. On hard courts, small adjustment steps are emphasized.

18.5.2.2 Suicides, 2 Court

This drill is the same as described above, except the exercise is completed twice on 1-court or once on a 2-court bank if available.

Fig. 18.37 Up-up, back-back, sprint to ground stroke, sprint to volley, forehand and backhand



18.5.2.3 Net Zigzag

Five cones are placed in a zigzag pattern from the baseline to the net as shown in Fig. 18.38. 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. 18.38, 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.

18.5.2.4 Forehand and Backhand Wide Continuous Hitting

The athlete begins in the center of the baseline behind a cone. The instructor feeds balls to the forehand and backhand, wide toward each sideline, for the durations shown in Table 18.4. 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.

18.5.2.5 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

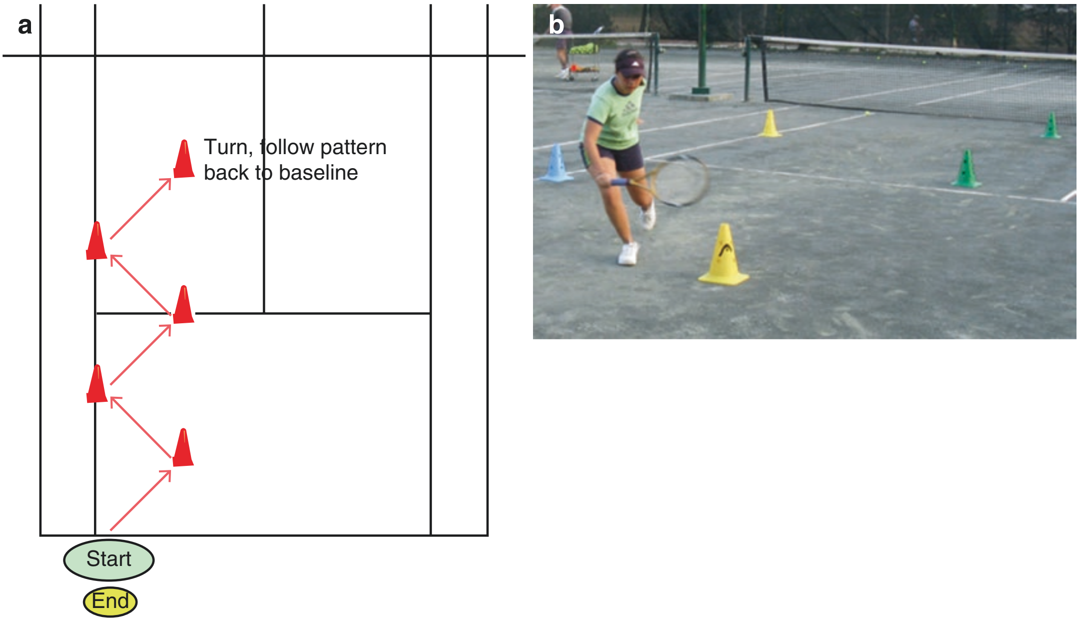


Fig. 18.38 Net zig-zag drill: (**a**) diagram and (**b**) simulated volley over last cone

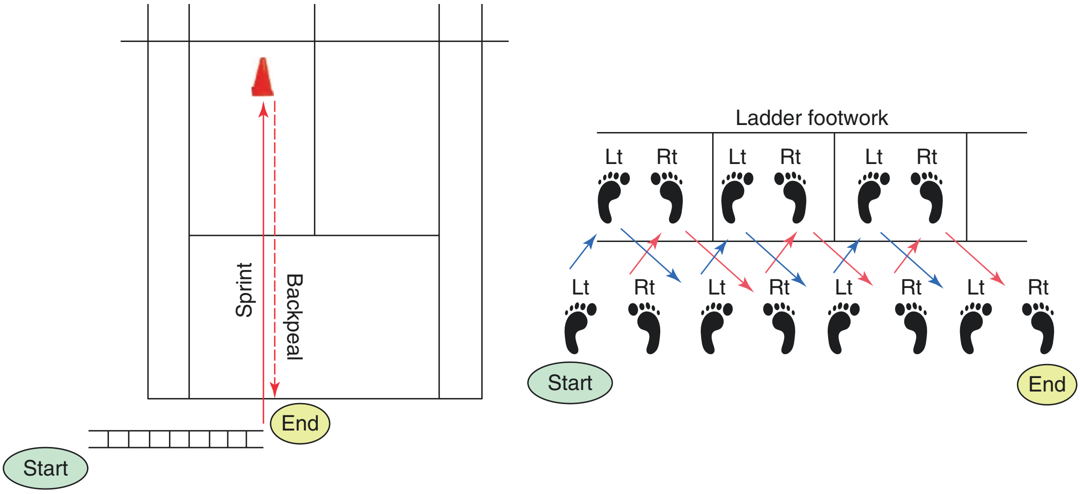


Fig. 18.39 Ladder: up-up, back-back, sprint to cone, backpedal

randomly feeds another round of ground strokes for 2 min without stopping. The athlete is reminded to focus on recovery footwork and to breathe continuously.

18.5.2.6 Sprint-Quick Feet-Listen to Instructor

See section "Sprint-Quick Feet-Listen to Instructor."

18.5.3 Ladders, Quick Feet, and Additional Jump Drills

18.5.3.1 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 (Fig. 18.39). 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 and then sprints forward to the cone, touches the cone with their racquet, and then runs backward in a controlled, balanced manner.

18.5.3.2 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.

18.5.3.3 Pattern Jumps

A series of ten jumps are performed in a four-square pattern configuration with tasks of increasing difficulty (Fig. 18.40). Each square is approximately 2 × 2 ft. (0.6 × 0.6 m). Two pattern jumps are performed each week (wk), beginning the second wk. of training, as the final jump/plyometric component. The player begins in box #1 and follows the numbers 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.

18.5.4 On-the-Court Strength Training

In addition to the strength training exercises described in Chap. 17, 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

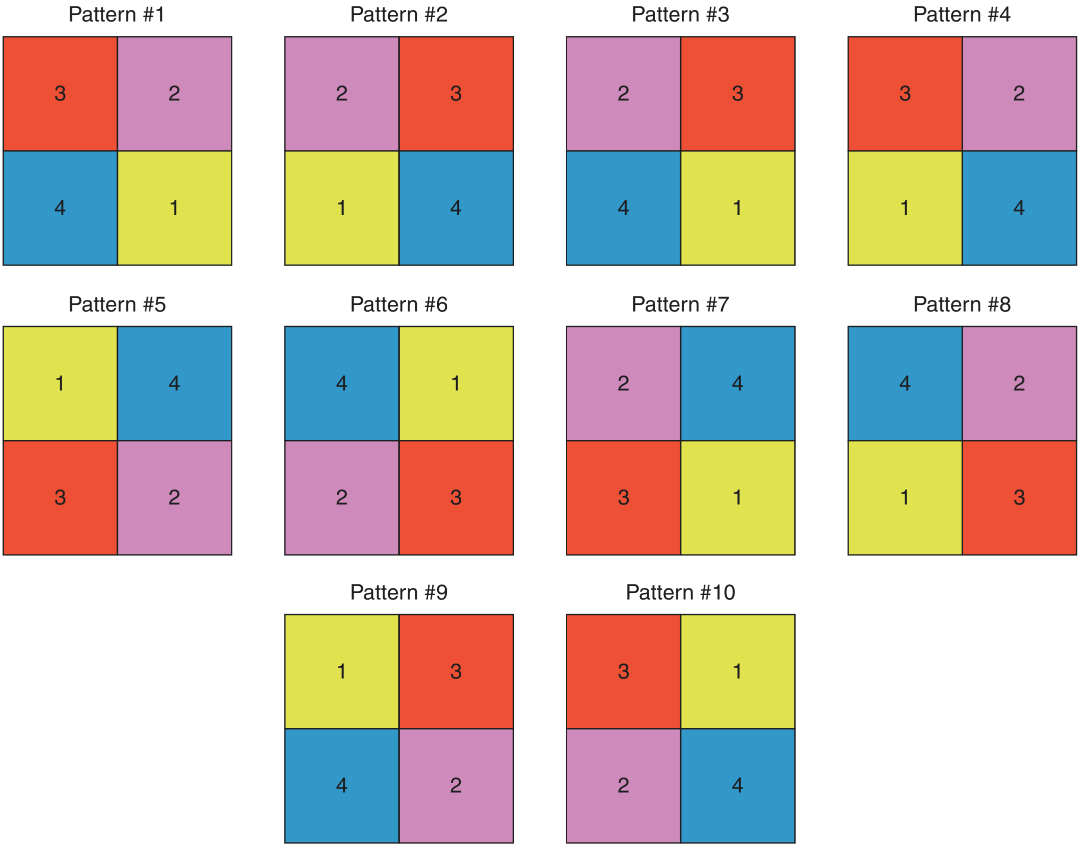


Fig. 18.40 Pattern jumps

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.

18.5.4.1 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. 18.41). 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.

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.

18.5.4.2 ETCH-Swing Forehand, Backhand, Serve

This drill uses the commercially available ETCH-Swing training device (The Etcheberry Experience, https://etcheberryexperience.com/

Fig. 18.41 Medicine ball forehand, backhand showing (**a**) exaggerated shoulder turn and (**b**) ball toss to partner

store/). 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. 18.42). 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 second serves.

18.5.4.3 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

Fig. 18.42 ETCH-swing forehand (**a**, **b**), backhand (**c**, **d**), serve (**e**, **f**)

Fig. 18.42 (continued)

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 18.4. 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. 18.43).

Fig. 18.43 Backward lunge with hand-held weights

18.5.4.4 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.

18.5.4.5 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.

18.5.4.6 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 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.

18.5.4.7 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 sit up "straighter" against the wall.

18.5.4.8 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.

18.5.4.9 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. 18.44a). 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. 18.44b.

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. 18.44c).

The medicine ball sideways core toss against the wall exercise is shown in Fig. 18.44d, 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.

Fig. 18.44 Medicine ball-wall exercises. (**a**, **b**) Tennis ball small circles. (**c**) Overhead dribble. (**d**, **e**) Sideways core toss against wall

18.6 Results of Programs

18.6.1 Soccer

A prospective study was conducted on 124 female soccer players aged 12–18 years [5]. The mean number of supervised training sessions attended was 15 ± 2 (range, 11–18). After training, significant increases were found in the video drop-jump test in the mean absolute knee separation distance and in the mean ankle separation distance ($P < 0.0001$) (Table 18.5; see Chap. 16 for test descriptions) indicating a more neutral lower limb alignment

Table 18.5 Summary of effect of Sportsmetrics sports-specific programs on athletic performance indices and lower limb alignment

Program	Participants	Test[a]	Pre-train[b]	Post-train[b]	Difference	*P* value	Effect size
Soccer	124 girls	Drop-jump test					
	Aged 12–18 years	Absolute knee separation distance (cm)	14.6 ± 3.6	23.1 ± 6.4	8.5	<0.0001	1.64
	High school, club players	Normalized knee separation distance (%)	35.9 ± 7.4	54.2 ± 13.7	18.3	<0.0001	1.66
		T-test (s)	12.05 ± 0.87	11.31 ± 0.69	−0.75	<0.0001	0.94
		Multi-stage fitness test (mL kg^{-1} min^{-1})	37.9 ± 4.5	40.1 ± 4.7	2.2	<0.0001	0.48
		37-m sprint (s)	6.11 ± 0.43	5.99 ± 0.38	−0.12	0.02	0.3
		Vertical jump height, 2-step approach (cm)	40.7 ± 8.9	42.1 ± 8.3	1.3	0.04	0.16
Basketball	57 girls	Drop-jump test					
	Aged 14–17 years	Absolute knee separation distance (cm)	18.5 ± 7.4	31.8 ± 10.36	13.2	<0.0001	1.48
	High school players	Normalized knee separation distance (%)	44.9 ± 17.2	74.2 ± 18.8	29.2	<0.0001	1.63
		Multi-stage fitness test (ml kg^{-1} min^{-1})	34.6 ± 4.5	39.5 ± 5.7	4.9	<0.0001	0.95
		Vertical jump height, countermovement (cm)	26.2 ± 12.3	28.5 ± 12.0	2.3	<0.0001	0.19
Volleyball	34 girls	Drop-jump test					
	Aged 14–17 years	Absolute knee separation distance (cm)	21.1 ± 8.2	25.9 ± 5.2	4.7	0.002	0.68
	High school, club players	Normalized knee separation distance (%)	56.3 ± 19.1	63.3 ± 12.7	6.9	0.04	0.43
		Multi-stage fitness test (ml kg^{-1} min^{-1})	39.4 ± 4.8	41.4 ± 4.0	2.2	<0.001	0.45
		Sit-up test (no. reps)	37.7 ± 5.3	40.5 ± 5.9	2.7	0.03	0.5
		Vertical jump height, countermovement (cm)	40.1 ± 7.1	41.5 ± 4.5	1.2	0.05	0.24
Tennis	31 girls	1-court suicide (s)	18.55 ± 1.68	16.04 ± 1.23	−2.51	<0.0001	1.7
	11 boys	Abdominal endurance test (s)	87 ± 56	162 ± 98	74	<0.0001	0.94
	Aged 11–18 years	Baseline backhand (no. reps)	8.5 ± 0.9	9.2 ± 0.7	0.7	<0.0001	0.88
	Tournament, high school players	Baseline backhand, total distance (m)	42.8 ± 4.6	46.3 ± 3.6	3.5	<0.0001	0.85
		Service line (no. reps)	22.4 ± 2.9	24.5 ± 2.2	2.1	<0.0001	0.82
		Service line, total distance (m)	89.4 ± 11.8	97.8 ± 8.9	8.4	<0.0001	0.8
		Baseline forehand (no. reps)	8.6 ± 1.0	9.3 ± 0.8	0.7	<0.0001	0.77
		Baseline forehand, total distance (m)	43.2 ± 5.1	46.8 ± 4.2	3.6	<0.0001	0.77
		Single-leg hop, right leg (cm)	128.2 ± 28.5	141.8 ± 22.8	13.7	0.0004	0.53
		Single-leg hop, left leg (cm)	129.5 ± 27.1	138.3 ± 26.0	8.9	0.0007	0.33
		Single-hop triple crossover hop, right leg (cm)	340.7 ± 71.9	373.6 ± 70.1	32.8	0.006	0.46
		Single-hop triple crossover hop, left leg (cm)	340.5 ± 77.6	374.3 ± 78.4	33.8	0.004	0.43

NS not significant
See Chap. 16 for test descriptions
Mean ± standard deviation

on landing. A significant improvement was observed in the mean *T*-test agility score ($P < 0.0001$), with 87% demonstrating better scores after training. Significant improvements were observed in the multi-stage fitness test (MSFT) in mean estimated maximal aerobic power (VO_2max) ($P < 0.0001$). Sixty-nine percent of the subjects improved in this test. Although the 37-m sprint score improved from 6.11 ± 0.43 s to 5.99 ± 0.38 s ($P = 0.02$), the effect size was small (0.30). A significant improvement was found in the two-step approach vertical jump test ($P = 0.04$), but the effect size was also small (0.16). No subject sustained an injury that resulted in loss of time training or that required formal medical attention.

18.6.2 Basketball

A prospective study was performed on 57 high school female basketball players aged 14–17 years [4]. All subjects attended at least 14 of the 18 training sessions. After training, significant increases were found in the video drop-jump test in the mean absolute knee separation distance and the mean normalized knee separation distance ($P < 0.0001$, Table 18.5). Improvement in the normalized knee separation distance was demonstrated in 91% of the subjects. A statistically significant improvement was found in the mean estimated $V0_2$max score ($P < 0.0001$). Eighty-nine percent of the subjects improved this score. A significant improvement was found in the vertical jump test ($P < 0.0001$), as 70% of the subjects increased their scores. 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.

18.6.3 Volleyball

A prospective investigation was conducted on 34 high school female volleyball players aged 14–17 years [3]. The mean number of training sessions attended was 15.3 ± 1.4. After training, significant increases were found in the video drop-jump test in the mean absolute knee separation distance ($P = 0.002$) and in the mean normalized knee separation distance ($P = 0.04$) (Table 18.5). A statistically significant improvement was found in the mean $V0_2$max score ($P < 0.001$). Seventy-three percent of the subjects improved this score. A significant improvement was found in the sit-up test ($P = 0.03$) and in the vertical jump test ($P = 0.05$), as 68% of the subjects increased their scores. No subject sustained an injury that resulted in loss of time training or that required formal medical attention.

18.6.4 Tennis

Two prospective studies were conducted in competitive junior tennis players [1, 28]. A total of 42 players (31 females, 11 males; mean age, 14 ± 2 years) completed at least 14 of the 18 training sessions. After training, significant improvements (and moderate to large effect sizes) were found for all tests (Table 18.5). 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 more than one training program. The number of training programs completed was 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 18.6).

Table 18.6 Improvements in speed, agility, and abdominal endurance tests in tennis players who completed more than one training program[a]

Training session	1-court suicide (s)			Baseline forehand (m)			Baseline backhand (m)			Service line (m)			Abdominal endurance (s)		
	Mean ± SD	*P*	ES	Mean ± SD	*P*	ES	Mean ± SD	*P*	ES	Mean ± SD	*P*	ES	Mean ± SD	*P*	ES
First	2.56 ± 1.17 (0.26–4.54)	<0.0001	1.63	4.6 ± 3.9 (0–15.1)	0.0004	1.01	4.8 ± 3.2 (−1.2–10.0)	<0.001	1.07	12.3 ± 11.3 (−4.1–45.1)	<0.001	1.30	84 ± 98 (−6–396)	0.005	1.02
Second	1.11 ± 1.07 (−1.00–3.10)	0.0003	1.36	2.6 ± 3.5 (−2.5–7.5)	0.01	0.73	1.6 ± 4.2 (−7.5–8.9)	NS	0.46	3.2 ± 9.9 (−16.4–26.7)	NS	0.32	70 ± 89 (−10–301)	0.01	1.20
Third	0.96 ± 0.032 (0.51–1.37)	0.004	0.73	3.8 ± 2.9 (0–7.5)	0.02	1.33	2.7 ± 2.3 (0–5.0)	0.02	0.89	11.6 ± 10.8 (3.9–32.9)	0.03	0.73	111 ± 86 (41–262)	0.02	0.95

NS not significant

[a] 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

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19 ACL Injury Prevention in Soccer: The Santa Monica Experience

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Abstract

This chapter summarizes current data related to the epidemiology of soccer-related injuries and injury prevention programs designed to reduce the risk of these injuries. Studies regarding the Prevent Injury and Enhance Performance (PEP) program and the 11+ program (FIFA 11+) are summarized. A newer study on the video analysis of ACL injury mechanisms is detailed. Compliance with training is demonstrated to be a critical component of injury prevention efforts.

19.1 Introduction

Soccer is the most widely played sport among both men and women, with approximately 300 million registered players globally [1–3]. It is currently 22nd (now 23rd) the third most popularly played sport, with over 13 million Americans participating at the youth and adult levels [4, 5]. Major League Soccer (MLS) is currently in its 23rd season and has grown to 20 (now 23 teams) professional teams within the USA and Canada [6]. In the high school setting, there are approximately 412,000 high school male and 372,000 high school female soccer players [7]. In the collegiate setting, there are approximately 27,000 collegiate male and 33,000 female collegiate soccer players participating in National Collegiate Athletic Association (NCAA) soccer in the USA [8, 9]. The number of athletic participants is increasing annually, and this increase imparts a multitude of positive effects with respect to physical health, psychological health, and overall wellness and is influential in decreasing the onset of illness and systemic disease. The inherent risks associated with soccer participation are well documented [10–19]. In the last two decades, numerous attempts have been made to gain a fuller understanding regarding the mechanism of soccer-related injury and how researchers can reduce the incidence of such injuries [13, 18, 20–34].

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19.2 Epidemiology

Sports-related injuries are common. There are approximately 4.5 million sports-related injuries in the USA annually that occur in athletes aged 5–24, with two-thirds of the injuries originating in the lower extremity [35]. There have been numerous research studies published elucidating the incidence and prevalence of soccer-related injury in both males and females; recreational, amateur, and professional players; and youth, high school, collegiate, and adult players [17, 20, 31, 36–38]. A 2006 report generated by the US Consumer Product Safety Commission's injury surveillance database estimated that there were 186,544 soccer-related injuries; approximately 80% of these injuries occurred in players under the age of 24 [39, 40]. In the NCAA, soccer injuries have been shown to be interdependent of the level of play, player position, field type, timing of injury, and gender. The injury rate (IR) in the NCAA is 18.8/1000 athletic exposures (AE) in men's soccer games and 16.4 in women's soccer games [10, 41]. Women's soccer has the highest IR for any sport in the NCAA, and men's soccer is ranked as the third highest, falling closely behind football and wrestling [42]. In the high school setting, the injury risk in this younger cohort is identical to what is reported in the collegiate setting: the IR for girl's soccer ranks first and boy's soccer ranks third [43]. However, injury prevention programs have the inherent ability to statistically decrease the incidence of soccer-related injury, the severity of injury, and the time loss associated with such injury [32, 34, 44–46].

In the past two decades, many injury prevention efforts have focused solely on female athletes, particularly on prevention of anterior cruciate ligament (ACL) injury [23, 28, 34, 46–48]. Those efforts were well targeted, since the incidence of ACL injury in female athletes exceeds that of male counterpart [23, 49–51]. Recent work has expanded their focus to include all injuries that occur during soccer participation, the injury mechanisms related to the male soccer player, and how injury prevention programs have effectively reduced the rate of all soccer-related injury in the male cohort [17, 27, 32, 44, 52–55].

19.3 Injury Prevention in Soccer

Soccer-related injuries are a relatively common occurrence across gender, age, and level of competition. The high prevalence of soccer injuries has been well documented in the literature [56–65]. The impact of sports-related injury is complex and far-reaching, inflicting potential long-term physical, emotional, and financial consequences for the athlete to contend with long after their athletic career has finished. The rate of injury in soccer depends on several factors: age, level of competition, position on the field, field type, timing of injury, and gender [52]. Injuries incurred during soccer most commonly involve the lower extremity and most commonly occur in a game situation [16, 66–68]. In studies analyzing the injury rates of professional male soccer athletes, overall injury rate (IR) ranged from 6.2 to 13.2 injuries per 1000 athletic exposure (AE). The NCAA has long recognized the high rate of injury in men's and women's soccer. Men's game IR ranked third (18.8), and women's game IR ranked fourth overall (16.4), respectively, for all NCAA sports per 1000 AE. When the data was stratified by gender, women's soccer had the highest game IR overall. The IR for practices was equally high, with women ranking fourth (5.2/1000 AE) and men ranking fifth (4.3/1000 AE) compared to 13 other NCAA collegiate sports [42]. Furthermore, the male IR is four times higher in games compared with practices, and women's collegiate IR is three times higher in games than in practices [69]. Approximately 70% of game and practice injuries affected the lower extremities [70]. The shear magnitude of these injury rates, coupled with the increasing number of athletes participating in collegiate soccer, served as a meaningful impetus to actively intervene and attempt to reduce the current rate of injury, the severity of injury, and time loss associated with injury.

The earlier injury prevention programs primarily focused specifically on ACL injury reduction and prevention, namely, in the female athlete, due to the high rate of injury in this specific cohort [17, 28, 29, 34, 48]. Most of these neuromuscular training programs included a variety of strengthening, plyometric, and agility-based drills that addressed the major deficits most commonly associated with the female athlete that had sustained an ACL injury [47, 51, 71]. Several programs have been designed as dynamic warm-up programs in order to increase implementation fidelity and compliance, as well as to capitalize on the advantages associated with improved joint-position sense found as a component in well-designed neuromuscular training warm-up programs [28, 34, 72]. Despite the development and the evolution of the aforementioned programs, there is a continued and implicit need to address soccer-related injury in totality and for an enhanced understanding of the most common mechanisms of injury in soccer.

19.4 The PEP Program

Many of these aforementioned intervention programs require special equipment, specialized training, or a significant time commitment. In 1999, an expert panel convened by the Santa Monica Sports Medicine Research Foundation (SMSMF) designed the Prevent Injury and Enhance Performance (PEP) program in order to address the escalating rate of ACL injury in the female athlete. This prevention program (Table 19.1) consists of five components: general warm-up activities, strengthening, plyometrics, sport-specific agilities, and stretching to address potential deficits in the strength and coordination of the stabilizing muscles around the knee joint. It was designed as a direct replacement to the traditional soccer warm-up so that the desired activities could be performed on the field during practice without specialized equipment for ease of implementation and socioeconomic feasibility. The program consists of an educational videotape or DVD that demonstrates proper and improper biomechanical technique of each prescribed therapeutic exercise. An entire team can complete the 19 components in less than 20 min.

19.4.1 Methodology

The PEP program was implemented in two age cohorts in female soccer players: 14–18 years old and 18–23 years old [28]. The program was a 20-minute dynamic warm-up that preceded the normal training sessions or games and required minimal equipment (only soccer cones and a ball). Each team in the intervention group received an educational video depicting the warm-up program and a supplemental literature packet. In addition, each coach attended a mandatory league meeting in which the PEP program was introduced and the research study parameters were described at length. The video provided education on three basic warm-up activities, three strengthening exercises, five plyometric activities, three soccer-specific agility drills, and five stretching techniques for the trunk and lower extremity to be performed after training. There was also a demonstration on how to perform these activities with proper biomechanical technique [28].

Table 19.1 The Santa Monica Orthopaedic and Sports Medicine Research Foundation

Warm-up
Jog line to line (cone to cone)
Shuttle run (side to side)
Backward running
Strengthening
Walking lunges
Russian hamstring
Single toe raises
Plyometrics
Lateral hops over cone
Forward/backward hops over cone
Single-leg hops over cone
Vertical jumps with headers
Scissors jump
Agilities
Shuttle run with forward/backward running
Diagonal runs (3 passes)
Bounding run (44 yds)
Stretching (this portion of the program is to be completed at the end of the regular training session)
Calf stretch
Quadriceps stretch
Figure four—piriformis stretch
Hamstring stretch
Inner thigh adductor stretch
Hip flexor stretch

[a] Training session per coaching staff: approximately 1–1.5 h

19.4.2 Results

In the 2000 soccer season, a total of two ACL tears confirmed by MRI were reported for the intervention group for an incidence of 0.05 ACL injuries/1000 AE. Thirty-two ACL tears were reported for the control group (0.47/1000 AE). These results indicate an 88% overall reduction in ACL injury per individual athlete compared with a control athlete matched for skill and age. In year 2 of the study, four ACL tears were reported in the intervention group, with an incidence of 0.13/1000 AE. Thirty-five ACL tears were reported in the control group, with an incidence of 0.51/1000 AE. This corresponds to an overall reduction of 74% in ACL tears in the intervention group compared with a control group matched for age and skill [28]. The limitations of this study include non-randomization of the subjects, no consistent direct oversight of the intervention, and compliance measurements that were only completed in a small subset of intervention teams.

19.4.3 Additional Studies Using the PEP Program

Following the initial intervention study, a randomized controlled trial was conducted in Division I NCAA women's soccer teams [23]. Sixty-one teams with 1429 athletes completed the study: 854 athletes in 35 control teams and 575 athletes in 26 PEP teams. After one season, there were 7 ACL injuries in the PEP intervention athletes and 18 in the control group (IR 0.14 and 0.25, respectively; $P = 0.15$). A 100% reduction in practice contact and noncontact ACL injuries occurred, with no injuries reported in the intervention athletes compared with six in the control athletes (IR 0.0 and 0.10, respectively; $P = 0.01$). During game situations, the IR difference was not significant. Noncontact ACL injuries occurred at over three times the rate in control athletes ($n = 10$, IR 0.14) compared with intervention athletes ($n = 2$, IR 0.04; $P = 0.06$). Control athletes with a previous history of ACL injury had a recurrence five times more often than those in the intervention group (IR 0.10 and 0.02, respectively; $P = 0.06$); this difference reached significance when limited to noncontact ACL injuries during the season (0.06 and 0.00, respectively; $P < 0.05$). There was a significant difference in the rate of ACL injuries in the last 6 weeks of the season, with a 100% reduction in contact and noncontact ACL injuries (intervention IR 0.00 and control IR 0.18; $P < 0.05$). This supports the concept that it takes 6–8 weeks for a biomechanical intervention program to have a neuromuscular effect [23].

Pfeiffer et al. [33] used two of the five components of the PEP program in a prospective randomized controlled trial in high school volleyball, basketball, and soccer athletes for two seasons. The intervention group participated in a plyometric-based exercise program twice a week throughout the season that was completed after training. A total of 1439 athletes (862 in the control group and 577 in the intervention group) were monitored. There were six confirmed noncontact ACL injuries: three in the intervention group and three in the control group. The incidence of noncontact ACL injuries was 0.167 per 1000 AE in the intervention group and 0.078 in the control group, yielding an odds ratio of 2.05 ($P > 0.05$). This research may demonstrate that isolating certain components of a comprehensive neuromuscular training program and completing those components post-training, ostensibly in a physiological and neuromuscular fatigued state, may directly nullify the positive impact and efficacy of an injury prevention program [33].

19.4.4 Conclusions

The results of this study indicated that implementing a neuromuscular training program, such as the PEP program, might significantly reduce the incidence of ACL injuries in the female athlete. Based on these findings, SMSMF contended that a prophylactic training program focusing on developing neuromuscular control of the lower extremity through strengthening exercises, plyometrics, and sports-specific agilities may address the proprioceptive and biomechanical deficits that are demonstrated in the high-risk female athletic population. This initial study laid the groundwork for the foundation's next steps: studying the biomechanical implications of instituting the PEP program, identifying the mechanism of ACL injury, and, finally, determining a precise neuromuscular intervention program that would specifically counteract the unopposed forces around the trunk and lower extremity to further decrease the incidence of severe ligamentous injury.

Critical Points

- The PEP program is a dynamic warm-up designed to address the biomechanical deficits most commonly associated with ACL-injured athletes.
- The program should be completed in its entirety and prior to training/game in a non-fatigued state. When only used partially and/or in post-training, the effects of the intervention were nullified.
- The program can be initiated in youth athletes over the age of 8 years.
- The program has been tested in high school-aged and collegiate soccer players and has been shown to reduce ACL injury significantly in each of those respective cohorts.

19.5 The 11+ Program

Over the last decade, as researchers continued to unravel the mechanism of injury and pathokinematics surrounding ACL injury, prevention programs garnered serious support in the field of sports medicine. Both the International Olympic Committee and the Féderation Internationale de Football Association (FIFA) emphasize the protection of athletes' health as a major objective, and in 1994, FIFA established its own Medical Assessment and Research Center (F-MARC) in order "to prevent football injuries and to promote football as a health-enhancing leisure activity, improving social behavior" [73]. On the basis of previous prevention programs including PEP, F-MARC attempted to create a simple and time-efficient preventive program to reduce the most common football injuries including ankle sprains, hamstring and groin strains, and ligament injuries in the knee. As a result, in 2003, an international group of experts under the tutelage of F-MARC created The 11, a program that was comprised of ten evidence-based or best-practiced exercises, and required no equipment other than a ball that could be completed within 10 to 15 min as a matter of routine (F-MARC, 2009). However, in a randomized controlled trial, the Oslo Sports Trauma and Research Center (OSTRC) examined the effect of "The 11" over one season among 2000 female players aged 13–17 and found no difference in injury risk between the intervention group and the control group. Furthermore, OSTRC found that the compliance of the intervention group was too poor in order to identify a statistically significant effect of the program [46].

To improve upon both the preventive impact of The 11 and the compliance of the program, OSTRC, F-MARC, and SMSMF reconvened and developed a new program in 2006, termed the 11+. This program was predicated on key exercises from the PEP program and The 11 that were shown to have statistically significant impact in previous studies [23, 28]. The 11+ is a comprehensive program encompassing cardiovascular and preventive exercises that focus on core and leg strength, balance, and agility and has a progression of three levels with increasing difficulty to provide variation and increases in difficulty (Table 19.2). It takes approximately 20 min to complete and requires a minimum of equipment (a set of cones and soccer balls). Similar to the PEP program, the FIFA 11+ is time-efficient and inherently promotes compliance because it directly replaces the customary warm-up [34, 73, 74]. It was designed as an alternative warm-up program to address lower extremity injury incurred in the sport of soccer for athletes over the age of 14 [34, 74].

There are 15 exercises divided into three separate components: running exercises (8 min) that encompass cutting, change of direction, decelerating, and proper landing techniques; strength,

Table 19.2 The 11+ training program

Part	Time to complete (min)	Exercise		
1 Running exercises	8	1. Running straight ahead 2. Running hip out 3. Running hip in 4. Running circling partner 5. Running shoulder contact 6. Running quick forward and backward		
		Level 1	**Level 2**	**Level 3**
2 Strength plyometrics balance	10	7. The bench: static 8. Sideways bench: static 9. Hamstrings: beginner 10. Single-leg stance: hold the ball 11. Squats: with toe raises 12. Vertical jumps	7. The bench: alternate legs 8. Sideways bench: raise and lower hip 9. Hamstrings: intermediate 10. Single-leg stance: throw ball with partner 11. Squats: walking lunges 12. Lateral jumps	7. The bench: one leg lift and hold 8. Sideways bench: with leg lift 9. Hamstrings: advanced 10. Single-leg stance: test your partner 11. Squats: one-leg squats 12. Box jumps
3 Running exercises	2	13. Running: across the pitch 14. Running: bounding 15. Running: plant and cut		

Fig. 19.1 Russian hamstring

Fig. 19.2 Bounding agility run

plyometric, and balance exercises (10 min) that focus on core strength, eccentric control, and proprioception (Figs. 19.1, 19.2, and 19.3) and running exercise (2 min) to conclude the warm-up and prepare the athlete for athletic participation. There are three levels for each specific exercise (level 1, level 2, level 3) that increase the difficulty for each respective exercise. This allows for both individual and team progression throughout the course of the competitive season. In this specific study [34], the FIFA 11+ program served as the intervention program over the course of one competitive collegiate soccer season. The warm-up was suggested to be used three times per week for the duration of the season.

Fig. 19.3 Single-leg eccentric squat

19.5.1 History of the 11+

The FIFA 11+ program was first tested in female soccer players in Norway. Soligard et al. [34] completed a cluster, randomized controlled trial in 125 female youth soccer clubs in Norway (aged 13–17): 65 teams ($n = 1055$) in the intervention group (IG) and 60 teams ($n = 837$) in the control group (CG) followed the protocol for one season (8 months). During the season, 264 players had relevant injuries: 121 players in the IG and 143 in the CG (rate ratio 0.71, 95% CI 0.49–1.03). In the IG, there was a significantly lower risk of injuries overall (rate ratio 0.68, 95% CI 0.48–0.98), overuse injuries (rate ratio 0.47, 95% CI 0.26–0.85), and severe injuries (rate ratio 0.55, 95% CI 0.36–0.83). This study indicated that a structured warm-up program can prevent injuries in young female soccer players [34].

In a small cohort study conducted in men's collegiate soccer in the USA, Grooms et al. [44] used the FIFA 11+ intervention for one Division III soccer team in 41 players 18–25 years of age. The first season served as the referent season (REF), and the second season served at the intervention assessment (IG). The IR in the REF was 8.1 injuries/1000 AE with 291 days lost; the IR in the IG season was 2.2 injuries/1000 AE with 52 days lost. The IG demonstrated reductions in the relative risk (RR) of lower extremity injury of 72% (RR = 0.28, 95% CI 0.09, 0.85) and time lost to lower extremity injury ($P < 0.01$). Despite the small sample size, there was a statistically significant reduction in injury rate and time loss to injury. The researchers noted excellent compliance and adherence to the program and benefited from direct oversight from an athletic trainer at every exposure [44].

A recent study investigated the efficacy of the FIFA 11+ in the male soccer cohort in African Lagos Junior League. Owoeye et al. [32] used the FIFA 11+ intervention in a cluster randomized trial in 20 teams over the course of 6 months ($n = 416$ players; intervention group [IG] 212 players, control group [CON] 204 players). In total, 130 injuries were recorded in 104 (25%) of the 416 players. The FIFA 11+ program significantly reduced the overall rate of injury in the IG group by 41% (RR = 0.59, 95% CI 0.40–0.86; $P = 0.006$) and all lower extremity injuries by 48% (RR = 0.52, 95% CI 0.34–0.82; $P = 0.004$). However, the rate of injury reduction based on secondary outcomes mostly did not reach the level of statistical significance [32].

The FIFA 11+ program has been shown to be an efficient means of achieving optimal physiological readiness for sport [1, 75]. The program has also been shown to increase muscle activation in the abdominal rectus and gluteus medius and minimus immediately after completing the program, corroborating its effect on core activation [45]. Daneshjoo et al. [21] analyzed the effect of the FIFA 11+ on knee strength in male competitive soccer players. Quadriceps and hamstring strength was assessed after 24 sessions of the FIFA 11+ program in 36 U-21 male soccer players. Concentric quadriceps peak torque (PT) increased 27.7% at 300°/s in the dominant leg ($P < 0.05$). Concentric hamstring PT increased in the dominant leg by 22%, 21.4%, and 22.1% at 60°/s, 180°/s, and 300°/s, respectively. Concentric hamstring PT increased in the non-dominant leg compared to the control group by 22.3% and 15.7% at 60°/s and 180°/s, respectively.

19.5.2 The 11+ in Male Collegiate Soccer Players

A prospective cluster randomized controlled trial was conducted in Division I (DI) and Division II (DII) NCAA men's soccer teams [76]. Every athletic director, head soccer coach, and head athletic trainer from each institution with a men's college DI or DII soccer program ($n = 396$) was contacted via a formal letter, an email that reiterated the written letter, and a direct phone call. The letter and email included a hyperlink for video clips that featured former and current prominent US soccer players and a coach who discussed the nature and importance of prevention in the sport of soccer (http://vimeo.com/25708967 and http://vimeo.com/25708960). Prior to randomization, player consent was obtained, and a documentation of coaching understanding was signed by each institution to ensure that there was a thorough understanding of the expectations of study participation. Upon randomization of the enrolled institutions, the intervention group (IG) received an instructional FIFA 11+ DVD, prevention manual, and explanatory placards describing the FIFA 11+ intervention at length (www.f-marc.com/11plus).

The average utilization of the FIFA 11+ in the IG was 32.8 ± 12.1 doses over the course of the season. There was no significant difference between the age of the injured athletes (mean, 20.4 ± 1.6 year IG and 20.7 ± 1.5 year CG), nor was there a difference in the number of injured athletes based on player position. There was a significantly higher proportion of athletes injured in the CG ($n = 665$, 70%, IR = 15.04/1000 AE) compared with the IG ($n = 285$, 30%, IR = 8.09/1000 AE; $P < 0.001$). The CG had a significantly higher average number of injuries per team than the IG (19.56 ± 11.01 and 10.56 ± 3.64, respectively; $P < 0.001$).

There was a significantly higher number of days missed due to injury in the CG compared with the IG (13.02 ± 26.82 and 9.31 ± 14.83, respectively; $P = 0.007$). For each day missed in the IG group, 1.4 days were missed in the CG (OR = 1.40). The total number of days missed secondary to injury was 8776 in the CG compared with 2824 in the IG. There was no difference in either group for days missed based on field type.

A second Poisson regression was used for those who were in the IG to compare the number of days missed if the injury occurred on a day where the intervention was used. The model was significant (LR $\chi^2(2) = 6.02$, $P < 0.05$). There was a significantly higher number of days missed when the intervention was not used on day of injury than when it was used (10.65 ± 15.35 and 6.56 ± 10.44, respectively; $P = 0.039$). There was no difference on the number of days missed in the intervention group based on field type [76].

To determine if the 11+ program can reduce the incidence of ACL injury, a secondary analysis was completed [77]. The risk of ACL injury was lower in the teams that used FIFA 11+ compared with those that did not (1.1% [3 of 19] versus 2.4% [16 of 19]; RR, 0.24; 95% CI, 0.07–0.81; $P = 0.021$). When identifying the mechanism of ACL injury, there was a higher injury rate in the control group compared with the intervention group for both contact and noncontact mechanisms. For contact ACL injuries, there were fewer injuries in the athletes who used the FIFA 11+ compared with those who did not (0.35% [1 of 7] versus 0.90% [6 of 7]; RR, 0.21; 95% CI, 0.03–1.74; $P = 0.148$). For noncontact mechanisms, there were fewer ACL injuries in the athletes who used the FIFA 11+ compared with those who did not (0.70% [2 of 12] versus 1.5% [10 of 12]; RR, 0.25; 95% CI, 0.06–1.15; $P = 0.049$), representing a 75% decrease in noncontact ACL injury (Table 19.3) [77].

Critical Points

- The FIFA 11 program, the initial attempt at a global soccer injury prevention program, was largely unsuccessful secondary to ineffective content and decreased compliance within the intervention group.
- The protocol was revamped and renamed the 11+ program. The program has demonstrated a significant decrease in injury rates, severity of injury, and time loss due to injury in both male and female soccer players.

Table 19.3 Incidence of ACL injury in male soccer players: effect of FIFA 11+ program

	Control group			Intervention trained group			Rate ratio (95% CI)	
Injury characteristics		No./%	Injury rate		No./%	Injury rate		*P* Value
Total injuries	Total	665/100	15.04	Total	285/100	8.09	0.54 (0.49–0.59)	<0.001
	Game	392/58.9	28.77	Game	185/64.9	16.92	0.59 (0.52–0.68)	<0.001
	Practice	273/41.1	8.93	Practice	100/35.1	4.01	0.46 (0.38–0.57)	<0.001
Knee injuries	Total	102/15.3	2.307	Total	34/11.9	0.965	0.42 (0.29–0.61)	<0.001
Mechanism of ACL injuries	Total	16/2.41	0.362	Total	3/1.05	0.085	0.24 (0.07–0.81)	0.021
	Contact	6/0.90	0.135	Contact	1/0.35	0.028	0.21 (0.03–1.74)	NS
	Noncontact	10/1.50	0.226	Noncontact	2/0.70	0.057	0.25 (0.06–1.15)	0.049
ACL injuries game versus practice	Game	12/1.80	0.881	Game	3/1.05	0.283	0.31 (0.09–1.11)	NS
	Practice	4/0.60	0.131	Practice	0	0	0.14 (0.01–2.59)	NS
ACL injuries by position	Defender	5/0.75	0.339	Defender	1/0.35	0.085	0.25 (0.03–2.15)	NS
	Forward	5/0.75	0.339	Forward	0	0	0.11 (0.01–2.07)	NS
	Midfielder	6.0/0.90	0.54	Midfielder	2/0.70	0.227	0.42 (0.06–2.07)	NS
	Goalkeeper	0	0	Goalkeeper	0	0	1.26 (0.03–63.36)	NS
ACL injuries by division	Division I	7/1.05	0.317	Division I	2/0.70	0.114	0.30 (0.06–1.45)	NS
	Division II	9/1.35	0.407	Division II	1/0.35	0.057	0.12 (0.02–0.93)	0.042

CI confidence interval
From Silvers-Granelli et al. [77]

- This program is an on-the-field warm-up designed, similarly to the PEP program, to be completed prior to training or a game. It takes approximately 15–20 min to complete and does not require any additional equipment.
- The 11+ program has been also shown to significantly reduce the rate of ACL injury in the male soccer player.

19.5.3 Conclusions

The results suggest that consistent utilization of a neuromuscular training program, such as the 11+, may impart a protective benefit to the soccer athlete by achieving an optimal state of physiological preparedness for soccer competition and sufficient biomechanical training to offset the risk of injury associated with soccer participation.

19.6 Video Analysis of ACL Injury Mechanism

Recent studies have analyzed injury mechanisms in male and female soccer players to further delineate the specific kinetics and kinematics directly involved in the mechanism of injury [67, 78]. After analyzing videos of male and female athletes incurring a soccer-related injury, we have begun to establish the high-risk positioning most commonly associated with the sport, namely, defensive play with the involved player at or near full hip and knee extension [67, 78]. As research continued to confirm a discrepancy between the ACL injury rates of males and females, experts from SMSMF and Washington University Orthopedics next undertook a gender-based study to elucidate the mechanism of injury using video analysis. While there had been video analyses of ACL injuries in basketball, handball, Australian football, and alpine skiing, no such study existed at the time for soccer [30, 79, 80]. Video analysis offered a way to accurately describe the game situation and biomechanics of injury and provide a fuller understanding of the underlying risk factors that may be amenable to prevention efforts. The researchers used this tool to test the hypothesis that these risk factors differ between male and female soccer athletes.

19.6.1 Methodology

Fifty-five videos of ACL injuries in 32 male and 23 female soccer players were collected and analyzed [67]. Most injuries were incurred by professionals (22 males, 4 females) or collegiate level players (8 males, 14 females), with the remainder of the injuries occurring in high school and youth players. Visual analysis of each case was performed to describe the injury mechanisms in detail (game situation, player behavior, lower extremity alignment, and kinematics). The goal was to identify the most frequent game situation in which the injury occurs and to determine the most common mechanisms by which ACL tears occur. The analysis for game situation included whether the player was playing an offensive or defensive role, the athletic action of the player (heading, passing, receiving the ball, tackling, etc.), whether the player was in control of the ball, and the location on the field where the injury occurred.

The mechanics of the ACL injury were studied in a systematic approach. The side of the injury and whether the injury was via contact or noncontact were recorded. Contact injuries were further divided into two separate subcategories revealing whether the injury was caused by direct contact to the lower extremity or indirect contact to other parts of the body, which influenced the injury by adding perturbation. Noncontact injuries were also examined to determine whether there was an opponent or another player in close proximity (within 1 m of the injured player) during the injury [67].

19.6.2 Results

The majority of ACL injuries occurred when the opposing team had the ball and the injured athlete was defending (73%). Females were more likely to be defending when they injured their ACL than males (87% and 63%, respectively; $P = 0.045$). The most common playing action was tackling (51%), followed by cutting (15%). More than half of injuries occurred due to a contact mechanism (56%). There was a trend toward a greater percentage of ACL injuries occurring via contact in females compared with males (61% and 53%, respectively; $P = 0.06$). ACL injuries that occurred when tackling usually involved contact (79%). In females, 80% of ACL injuries while tackling involved contact compared with 54% in males, but the difference was not significant ($P = 0.13$). For the vast majority of noncontact injuries (83%), an opposing player was within 1 or 2 yards of the injured athlete, but no direct contact occurred. Females were more likely than males to suffer a noncontact injury to their left lower extremity (54% and 33%, respectively; $P = 0.05$).

In addition to game situation results, biomechanical results were also collected. Injuries occurred during a variety of motions, including planting, landing, cutting, and decelerating. Athletes were usually moving forward or changing direction at the time of injury. The majority of contact injuries occurred with the athlete moving forward (80%). There were no significant differences between male and female athletes. Noncontact ACL injuries occurred most often with the hip flexed (88%) and abducted (83%), the knee in valgus (58%) and within 30° of full extension (71%), and the foot flat (58%). Similar patterns of joint position were seen with the contact injuries. There were no significant differences between male and female athletes.

19.6.3 Conclusion

These results demonstrated that soccer players most often injure their ACL when defending, specifically tackling, and females are more likely to injure their ACL while defending than are males. Overall, slightly more than half of the injuries occurred via a contact mechanism, although a significant proportion of noncontact injuries occurred with an opponent in close proximity. Because tackling is a reactive maneuver that can require last-minute adjustments in body position and technique, female athletes with poor neuromuscular control and suboptimal biomechanics may be more likely to react in a way that puts the ACL at risk for injury. Although a number of the ACL injuries that occurred during tackling were noncontact, the majority (79%) were contact in nature. Nevertheless, this could be an important finding with regard to potential injury prevention efforts, as proper tackling technique should be addressed during player development and training.

This study also confirmed results obtained previously by SMSMF and the Washington University research team: females have higher involvement of the non-dominant lower extremity in ACL tears compared to males [49]. Additionally, video analysis confirmed past studies suggesting that the ACL is the most vulnerable and most often injured when the knee is at near extension. This evidence was corroborated by a recent study conducted analyzing European soccer injuries [78]. Knee rotational moments combined with near knee extension is often described as the most common situation in which ACLs are injured in observational and retrospective analyses. Other studies have shown knee abduction and flat-footedness as possible mechanisms for ACL injury during tackling. Although this study did not provide ways to improve tackling techniques, it suggests that female soccer players may especially benefit from training focused on safe techniques for defending and tackling.

Critical Points

- Video analysis of injury mechanism provides important clinical insight into thoroughly understanding how injuries occur during athletic participation.
- Most ACL injuries seem to occur while assuming a defensive position, specifically tackling, with partial hip flexion, hip abduction, knee at or near full extension, and the foot planted.
- Furthermore, this analysis provides critical information on how we can improve upon existing injury reduction efforts.

The continued delineation of the risk factors associated with sports-related injury will further the clinicians' ability to elucidate and refine a comprehensive intervention program to effectively decrease the injury rate in sport. Furthermore, the cohesive and consistent implementation of injury prevention and reduction protocols may be considered a very viable and cost-effective option to reducing the rate of soccer injury [81]. This knowledge can provide critical insight to help improve existing injury prevention protocols and secondary prevention strategies. Understanding the epidemiology and the mechanism of injury will allow researchers to refine and expound upon the current gold standard for injury prevention, thus decreasing the long-term deleterious sequelae commonly endured after incurring an injury [82].

19.7 The Role of Compliance

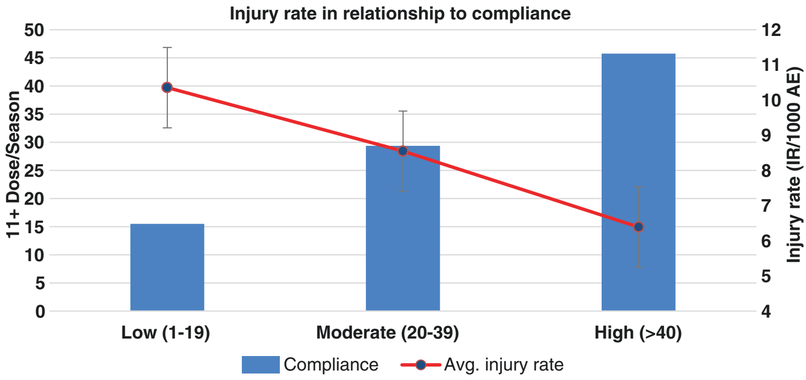
The role of compliance in injury prevention protocols has been well documented in the literature [76, 83, 84]. Current research has demonstrated an inverse correlation of injury rate and time loss due to injury with the compliance of effective injury prevention protocols [34, 83]. The scientific medical community continues to struggle with consistency in implementation, program fidelity, and therapeutic compliance across all levels of competitive soccer play. The manner in which the program is delivered may impact the rate or program adoption. Studies have analyzed how different program delivery systems impact compliance, and furthermore, the rate of injury [84]. Nations such as the USA and Canada and many regions of Asia and Africa are confronted by a large geographic expanse when it comes to efficient and feasible medical delivery and public health messaging. The concept of using instructional DVDs, online streaming resources, and smartphone applications may offer a cost-effective alternate delivery system for injury prevention protocols in the event that a skilled medical professional is unable to be present [45].

It is critical to understand the rationale of why coaches, teams, players, and parents choose to implement a scientifically vetted injury prevention program, or not too. Even though intervention programs have been shown to successfully reduce the rate of injury in competitive sport, the potential public health benefit and impact will not be realized if such interventions are not utilized consistently. Therefore, encouraging coaching and player motivation toward implementing injury prevention methodology into their training repertoire could have important public health ramifications and positive socioeconomic impacts on the aforementioned cohorts.

19.7.1 Compliance and Injury Rate

Upon analyzing the compliance of the 11+ in the male NCAA intervention study, there was an inverse relationship between compliance and overall injury rate [85]. There were 53 injuries in 4 low compliance (LC, 1–19 sessions) teams (mean 13.25, IR = 10.35 ± 2.21, RR = 1.62 [1.25–2.10], $P < 0.001$), 157 injuries in 14 moderate compliance (MC, 20–39 sessions) teams (mean 11.21, IR = 8.55 ± 2.46, RR = 1.34 [1.07–1.66], $P = 0.009$), and 75 injuries in 9 high compliance (HC, > 39 sessions) teams (mean 8.33, IR = 6.39 ± 2.71). There was a main effect within the groups for injury rate ($P = 0.04$). Upon post hoc analysis, the LC group (mean 13.25, 95% CI 9.82–16.68, IR = 10.3 5 ± 2.21) had a significantly higher injury rate than the HC group (mean 8.33, 95% CI 6.05–10.62, IR = 6.39 ± 2.71, $P < 0$ 0.001). The MC group (mean 11.21, 95% CI 9.38–13.05, IR = 8.55 ± 2.46) was not significantly different than the LC group, but was significantly greater than the HC group ($P = 0.009$). When examined as a continuous variable, compliance was significantly negatively related to injury rate ($b = -1.63$, $t = -3.20$, $P = 0.004$, $R^2 = 029$) (Fig. 19.4). This evidence reinforces what has been found by previous researchers; teams that demonstrate high compliance to the 11+ injury prevention program demonstrate lower injury rates throughout the competitive season [46, 83, 84]. There is an inverse correlation between high compliance and injury rate and severity of injury, which was reflected in fewer days lost due to injury. High compliance to the 11+ program resulted in fewer injuries and decreased severity of injury.

Fig. 19.4 Injury rates in relationship to compliance with the 11+ program



19.8 Overall Conclusions

The PEP and the FIFA 11+ programs have demonstrated the ability to decrease injury rates, including ACL, and improve overall team performance which supports the importance of the consistent implementation of injury prevention protocols in sport. Compliance is a critical component to the overall impact of the program; teams utilizing the program more consistently demonstrated lower injury rates and more success with respect to team performance.

By prospectively analyzing changes in soccer-specific movement patterns during competition, we are now able to more fully understand mechanism of injury and how the programs may be improved with respect to injury reduction and how the program imparts' a protective benefit. This information will guide future researcher on how to optimize injury prevention efforts, improve the content and efficiency of therapeutic prevention interventions, and to potentially identify high-risk athletes prospectively prior to a deleterious injury occurring. If these methods are implemented with optimal compliance and consistency early in an athlete's career, the overall risk of injury may be significantly reduced, and the long-term health and athletic career longevity may be extended through the later decades of life. Furthermore, the physical and financial longitudinal impact(s) of many sports-related injuries may be significantly mitigated, thus improving overall quality of life of the athlete, extending well past the tenure of a collegiate athletic career.

The overarching theme of this chapter was to establish the relevance of the PEP and the 11+ programs and to further highlight the biomechanical mechanism that allow these programs to be successful. These programs have demonstrated their ability to significantly reduce injury rates and the severity of injury. Program compliance is paramount; the more consistently the program was utilized, the greater the injury prevention benefit was imparted onto the athlete. The benefits of sport participation are numerous and far outweigh the risks. The likelihood of incurring an injury by virtue of participating in soccer should not be underestimated. As clinicians and researchers, we must collectively recognize the risks associated with sport and implement the prevention protocols that have been published to date. The information provided may help reduce the incidence of soccer-related injuries. We recognize the need for optimal program adherence and additional randomized controlled trials to continue to elucidate the etiology, mechanism of injury, and the need for continued biomechanical analysis of athletes to address the deficits that may inhibit their overall athletic performance and their ability to enjoy a functional, healthy, and active lifestyle.

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20 ACL Injury Prevention Warm-Up Programs

Frank R. Noyes and Sue Barber-Westin

Abstract

This chapter focuses on ACL injury prevention "warm-up" programs which have published data on ACL injury rates, athletic performance indicators, or neuromuscular factors. The goal is to determine if a recommendation may be made from the available peer-reviewed literature to date on the usage of these types of programs. Many ACL injury intervention programs designed to replace the traditional warm-up of several team sports have been tested. The potential advantages of these programs include improved practicality and compliance and decreased fatigue compared to training programs that are longer in duration. The possible disadvantages are failure to alter neuromuscular deficits, improve athletic performance indices, statistically reduce the noncontact ACL injury rate, and solve problems with long-term compliance issues.

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20.1 Introduction

Several anterior cruciate ligament (ACL) injury intervention programs designed to replace the traditional warm-up of handball, soccer, basketball, volleyball, and floorball teams have been designed and tested [1–17]. Training is accomplished either a few times a week or before each practice during the athletic season on the court or field of play for approximately 10–20 min. The potential advantages of these programs include improved practicality and compliance and decreased fatigue compared to training programs that are longer in duration. The possible disadvantages are failure to alter neuromuscular deficits, improve athletic performance indices, statistically reduce the noncontact ACL injury rate, and solve problems with long-term compliance issues.

This chapter focuses on warm-up programs which have published data on noncontact ACL injury rates in female athletes (Table 20.1) [8, 10–12, 15, 17–19], athletic performance indicators, or neuromuscular factors (Table 20.2) [2–5, 7, 13, 16, 21–24]. The goal is to determine if a recommendation may be made from the available peer-reviewed literature to date on the use of these types of programs.

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Table 20.1 Effect of ACL injury prevention warm-up programs on noncontact complete ACL injury rates in female athletes

Citation program	No. of athletes Type of sports No. of seasons	Duration of training	Program components	Compliance	Total no. of exposures		Number of noncontact ACL injuries (per 1000 athlete-exposures)			Comments, study limitations
					Trained	Control	Trained	Control	*P* value	
Mandelbaum [8] PEP	1885 trained, 3818 control Soccer, high school 2 seasons	20 min all practices during season	Plyometrics, strength, agility (Table 21.3)	NA	67,860	137,447	6 (0.09)	67 (0.49)	<0.0001	Not randomized, voluntary enrollment training, compliance with training NA
LaBella [18] KIPP	485 trained, 370 control Basketball, soccer, high school 1 season	20 min all practices during season	Plyometrics, strength, agility (Table 21.4)	NA	20,345	12,467	2 (0.10)	6 (0.49)	0.04	Injuries not sorted according to sport, only 37% of coaches invited participated
Gilchrist [19] PEP	583 trained, 852 control Soccer, collegiate 1 season	20 min all practices during season	Plyometrics, strength, agility	Mean no. sessions: 26 during season	35,220	52,919	2 (0.06)	10 (0.19)	0.066	Insufficient statistical power for ACL noncontact injuries
Walden [17]	2479 trained 2085 control Soccer, ages 12–17 1 season	15 min, 2 ×/wk during season	Plyometrics, strength, core stability	NA	NA	NA	3	7	NS	Total number of exposures not provided. Dropout frequency 21%
Kiani [6] HarmoKnee	777 trained, 729 control Soccer, high school	20–25-min, 2 ×/wk preseason, 1 ×/wk in-season	Plyometrics, strength, core stability (Table 21.5)	Preseason: 94% of teams 75–100% compliance In-season: 98% of teams 100% compliance	66,981	66,505	0	5 (0.07)	NS	Not randomized, low no. noncontact ACL injuries
Steffen [15] The "11"	1073 trained, 947 control Soccer, under-17 league 1 season	20 min, 15 consecutive sessions, then 1 ×/wk in-season	Plyometrics, strength, agility, balance (Table 21.6)	Program used in 52% of all training sessions	66,423	65,725	4 (0.06)	5 (0.08)	NS	Poor compliance completion training, insufficient statistical power for ACL noncontact injuries

Pasanen [10]	256 trained, 201 control Floorball teams, adult 1 season	20–30 min, 1–3 ×/wk during season	Agility, balance, plyometrics, strength, flexibility (Table 21.7)	Mean no. sessions: 31 (69%); 36% performed program regularly during season	32,327	55,019	3 (0.09)	3 (0.05)	NS	Insufficient statistical power for ACL noncontact injuries
Pfeiffer [12] KLIP	577 trained, 862 control Soccer, basketball, volleyball, high school 1 season	20 min, 2 ×/wk during season either beginning or end of training session	Plyometrics, agility (Table 21.8)	Mean no. sessions per player: 18 basketball 23 soccer 22 volleyball	17,954	38,662	3 (0.17)	3 (0.08)	NS	Not randomized, insufficient statistical power for ACL noncontact injuries
Petersen [11]	134 trained, 142 control Team handball, adult 1 season	10 min, 3 ×/wk preseason (8 wk), 1 ×/wk during season	Balance board, plyometrics (Table 21.9)	NA	NA	NA	1 (0.04)	5 (0.21)	NS	Not randomized, total number of exposures not provided, insufficient statistical power for ACL noncontact injuries

KIPP Knee Injury Prevention Program, *KLIP* knee ligament injury prevention program, *min* minutes, *PEP* Prevent Injury and Enhance Performance program, and *wk* week

Table 20.2 Effect of ACL injury prevention warm-up programs on athletic performance and neuromuscular indices in female athletes[a]

Citation, program, subjects	Duration training	Strength	Vertical jump	Speed, agility	Limb symmetry, balance	Neuromuscular indices
Rodriguez [20] PEP Soccer, adult Trained ($n = 20$)	20 min, 3 ×/wk during season	Increased isometric quadriceps and hamstrings strength ($P < 0.001$, ES = NA)	No improvement	NA	NA	No improvement
Vescovi [16] PEP Soccer, high school Trained ($n = 15$) Control ($n = 16$)	20 min, 3 ×/wk during season	NA	No improvement	9.1, 18.2, 27.3, 36.6-m sprint: no improvement; Illinois and pro-agility tests: 2–4% decline	NA	NA
Lim [7] PEP, modified Basketball, high school Trained ($n = 11$) Control ($n = 11$)	20 min all practices during season	Increased peak torque hip abductors 2.80 ± 0.40 to 3.17 ± 0.22 Nm/BW, hip extensors 5.51 ± 0.56 to 7.08 ± 1.11 Nm/BW, knee flexors 2.13 ± 0.33 to 2.36 ± 0.2 Nm/BW($P < 0.05$, ES = NA), hamstrings-quadriceps ratio 75.09 ± 5.69 to 67.97 ± 4.18% ($P = 0.02$, ES = NA)	No improvement	NA	NA	Rebound jump: improved knee flexion angle 92.66 ± 4.34° to 94.27 ± 3.44° ($P = 0.02$, ES = NA), knee separation distance 17.56 ± 2.92 to 20.81 ± 1.37 cm ($P = 0.004$, ES = NA), knee extension torque 236.96 ± 39.03 to 192.18 ± 12.37 ($P = 0.04$, ES = NA) No improvement knee internal rotation angle, knee abduction torque
Pollard [13] PEP Soccer, high school Trained ($n = 18$)	20 min, 2–3 ×/wk during season	NA	NA	NA	NA	Drop-jump: decreased hip internal rotation 7.1 ± 6.8° to 1.9 ± 7.8° ($P = 0.01$, ES = NA), increased hip abduction −4.9 ± 4.0° to −7.7 ± 4.7° ($P = 0.02$, ES = NA) No difference knee valgus, knee flexion angles

Steffen [21] The "11" Soccer, high school Trained ($n = 18$) Control ($n = 16$)	15 min, 3 ×/wk 2nd half of season	No improvement isokinetic lower extremity or isometric hip strength	No improvement	40-m: no improvement; speed dribbling and shooting distance: no improvement	NA	Countermovement and vertical jumps: no improvement knee valgus angle
Steib [22] The "11," modified for handball Adult handball Trained ($n = 21$) Control ($n = 20$)	15 min, 3 ×/wk for 15 wks	NA	NA	NA	Improved star excursion balance test all reach distances ($P < 0.001$, ES = NA), no improvement static balance	NA
Irmischer [5] KLIP College students, active Trained ($n = 14$) Control ($n = 14$)	20 min, 2 ×/wk during season	NA	No improvement	NA	NA	Drop-jump: reduced peak vertical ground reaction forces from 5.3 ± 1.0 to 3.9 ± 0.6 BW ($P = 0.0004$, ES = NA), rate force development from 0.11 ± 0.03 to 0.08 ± 0.02 BW/meters per s ($P = 0.02$, ES = NA)
Holm [4] Myklebust Elite team handball Trained ($n = 27$)	15 min, 3 ×/wk preseason (6–7 wk), 1 ×/wk during season	No improvement isokinetic quadriceps, hamstrings, hamstrings-quadriceps ratio	NA	NA	2-leg dynamic balance: improved index 924 ± 225 to 778 ± 174 ($P = 0.003$); 1-leg static balance and 3 hop tests: no increase	NA

(continued)

Table 20.2 (continued)

Chappell [2] Kerlan-Jobe Basketball, soccer Collegiate Trained ($n = 30$)	10–15 min, 6×/wk for 6 wks during season or preseason practice	NA	Increased 45.1 ± 14.1 to 48.8 ± 13.9 cm ($P < 0.001$, ES = NA)	NA	Single-leg timed hop: improved right leg 2.17 ± 0.4 to 2.03 ± 0.3 s ($P < 0.001$, ES = NA), left leg 2.17 ± 04. to 2.0 ± 0.2 s ($P < 0.001$, ES = NA)	Drop-jump: increased knee flexion foot strike 29.9 ± 9.0 to 35.1 ± 7.4° ($P = 0.003$, ES = NA) and stance phase 81.3 ± 10.5 to 86.9 ± 10.3° ($P = 0.006$, ES = NA), decreased peak knee flexion moment 0.739 ± 0.37 to 0.583 ± 0.30 N m ($P = 0.04$, ES = NA). No improvement 21 other factors
						Stop jump: decreased hip flexion 72.2 ± 11.0 to 68.0 ± 8.9°($P = 0.05$, ES = NA), maximum hip external rotation 20.0 ± 12.5 to 13.1 ± 13.8° ($P = 0.02$, ES = NA), dynamic knee valgus 0.863 ± 0.37 to 0.734 ± 0.31 N m ($P = 0.04$, ES = NA). No improvement 21 other factors
DiStefano [3] General and stratified ACL injury programs Soccer, 10–17 year Trained ($n = 90$ males, 83 females)	10–15 min, 3–4×/wk during season	NA	NA	NA	NA	Drop-jump: subjects with poor landing technique at baseline improved technique more than others
						High school-aged athletes improved more than pre-high school athletes
						No differences in change in landing technique after training between programs or gender

Lindblom [23] Walden Soccer, 12–16 year Trained ($n = 23$) Control ($n = 18$)	15 min, 2×/wk for 11 wks	NA	No improvement	No improvement 10, 20-m sprint, Illinois agility	Single-leg triple hop and star excursion balance: no improvement	NA

BW body weight, *ES* effect size, *KLIP* knee ligament injury prevention program, *MS* meters per second, *min* minutes, *NA* not assessed, *PEP* Prevent Injury and Enhance Performance, *wk* week

[a] All studies included only female athletes unless otherwise indicated

There are important qualifiers in the studies included in this chapter. None of the studies provided effect sizes (ES) in addition to *P* values when reporting effects of training on athletic performance and neuromuscular indices. The ES measures the magnitude of the effects of treatment and is especially relevant in studies with small sample sizes [25]. It is probable that some statistically significant findings ($P < 0.05$) reported in the studies in this chapter may have limited clinical relevance. Few studies conducted a prospective power calculation of the sample size required to discern a detectable difference (95% CI) regarding changes in athletic performance and neuromuscular indices resulting from the training program [7, 16, 21, 23]. All of the investigations analyzed preplanned tasks in a controlled laboratory setting. The effectiveness of these programs in improving potentially deleterious neuromuscular indices under reactive, unplanned athletic conditions is unknown.

Critical Points

- ACL injury prevention warm-up programs: handball, soccer, basketball, volleyball, and floorball
- Potential advantages: improved compliance and decreased fatigue
- Possible disadvantages: failure to improve neuromuscular deficits, athletic performance tests, and noncontact ACL injury rate

20.2 Programs: Components and Results

20.2.1 Prevent Injury and Enhance Performance (PEP)

Mandelbaum et al. [8] designed the Prevent Injury and Enhance Performance (PEP) program warm-up for female soccer players. The program consisted of three basic warm-up activities, five stretching exercises for the trunk and lower extremity, three strengthening exercises, five plyometric drills, and three soccer-specific agility activities (Table 20.3).

Table 20.3 Prevent Injury and Enhance Performance (PEP) program [8]

Exercise	Distance/duration
1. Warm-up	1 rep each
Jog line to line	45.7 m
Shuttle run	45.7 m
Backward running	45.7 m
2. Stretching	2 × 30 s each
Calf	NA
Quadriceps	NA
Hamstring	NA
Inner thigh	NA
Hip flexor	NA
3. Strengthening	
Walking lunges	18.3 m × 2
Russian hamstring	30 s
Single-toe raise	30 each leg
4. Plyometrics	30 s each
Lateral hops	5.08–5.24 cm cone
Forward hops	5.08–5.24 cm cone
Single-leg hops	5.08–5.24 cm cone
Vertical jumps	NA
Scissors jumps	NA
5. Agilities	1 rep each
Shuttle run	36.6 m
Diagonal run	36.6 m
Bounding run	36.6–45.7 m

cm centimeter, *m* meter, *NA* not applicable, *rep* repetition, *s* second

Two studies have been published to date regarding the ability of this intervention to reduce the incidence of ACL injuries. In the first study, 1885 trained high school female soccer players, and 3818 control players were followed over the course of 1 season [8]. A significant reduction was reported in the noncontact ACL injury incident rate between trained and control players (0.09 and 0.49 per 1000 athlete exposures [AE], respectively, $P < 0.0001$). The authors believed that the enhancement of neuromuscular control through the strengthening, plyometric, and agility exercises was an important factor in the study's success.

The next study entailed 583 female collegiate soccer athletes who participated in the intervention program and 852 players who served as controls [19]. The overall incidence of noncontact ACL ruptures per 1000 AE was 0.189 in untrained female athletes and 0.057 in trained female athletes ($P = 0.066$). The study lacked the statistical power to compare subgroups because of the smaller than expected number of noncontact ACL injuries reported (two in the intervention and ten in the control group). There was a significant reduction in the risk of all ACL injuries (contact and noncontact combined) in practice ($P = 0.01$) and during the second half of the season ($P = 0.02$). The authors noted that in many athletes, several weeks of training were required to demonstrate changes in strength, balance, and neuromuscular control and that a cumulative effect most likely explained these findings.

Several studies have assessed the effects of the PEP program on neuromuscular indices and athletic performance tests [7, 13, 16, 20]. Vescovi et al. [16] trained 15 high school soccer players three times per week for 12 weeks and reported no significant improvements in vertical jump height, speed, or agility. Lim et al. [7] trained 11 high school female basketball players for 8 weeks and reported significant improvements in isokinetic peak torques for hip abduction, hip extension, knee flexion, and the hamstrings-quadriceps ratio ($P < 0.05$). There was also a significant increase in knee flexion angle ($P = 0.02$) and knee separation distance ($P = 0.004$) on landing from a jump-rebound task. However, there were no significant improvements in vertical jump height, knee internal rotation angle, or knee abduction torque.

Pollard et al. [13] assessed the effects of the PEP program on hip and knee kinematic variables on a drop-jump test. Eighteen female soccer players aged 14–17 years completed the study, indicating they attended at least 80% of the training sessions during one season. Following training, a significant increase was noted in hip abduction (−4.9° versus −7.7°, $P = 0.02$), and a significant decrease was found in hip internal rotation (7.1° versus 1.9°, $P = 0.01$). There were no significant differences found in knee valgus or knee flexion angles.

20.2.2 Knee Injury Prevention Program (KIPP)

LaBella et al. [18] conducted the Knee Injury Prevention Program (KIPP) in high school female basketball and soccer players. Training was conducted by the team coaches in 20 min sessions before practices during one athletic season (Table 20.4). The incidence rate for noncontact ACL injuries was significantly lower in the 485

Table 20.4 Knee Injury Prevention Program (KIPP) [18]

Exercise	Week	Duration
Jog	All	2 laps around court or 1 lap around field
Dynamic motion	All	2 lengths of a basketball court (100 ft, 30.5 m)
Traveling exercises		
Jogging		
Skipping		
Carioca/grapevine		
Side shuffle with arm swing		
Sprint at 75% maximum		
High knee skipping		
High knee carioca		
Sprint at 100% maximum		
Backward jog		
Bear crawl		
Butt kickers		
Backward jog half-length, turn and sprint		
Diagonal skipping		20 each direction
Arm swings (forward, backward)		20 each direction
Trunk rotations		10 each direction
Leg swings, front-to-back and side-to-side		10 each leg
Strengthening exercises		NA

(continued)

Table 20.4 (continued)

Exercise	Week	Duration
Heel raises	All	
Squats	Wk 1–3	
Plank and side plank	All	
Push-ups	All	
Lunges		
Forward	Wk 1	
Lateral	Wk 2-on	
Diagonal	Wk 2-on	
Walking lunge: forward, lateral	Wk 3-on	
Prone lifts		
Lift arms and legs together	All	
Lift opposite arm and leg	All	
Knees flexed to 90°, heels together, hips externally rotated, lift arms and legs	Wk 2-on	
Plyometrics		
Ankle bounces	All	10 s (wk 1), 20 s (wk 2), 30 s (wk 3-on)
Tuck jumps	Wk 1–3	10 s (wk 1), 20 s (wk 2), 30 s (wk 3-on)
Jump in place, rotating 180°	Wk 1	10 s (wk 1), 20 s (wk 2), 30 s (wk 3-on)
Squat jumps	All	10 s (wk 1), 20 s (wk 2), 30 s (wk 3-on)
Broad jumps	Wk 1	5 reps
Front-to-back jumps	All	10 s (wk 1), 20 s (wk 2), 30 s (wk 3-on)
Side-to-side jumps	All	10 s (wk 1), 20 s (wk 2), 30 s (wk 3-on)
Bounding in place	Wk 1	10 s (wk 1), 20 s (wk 2), 30 s (wk 3-on)
Scissor jumps	Wk 2	10 s (wk 1), 20 s (wk 2), 30 s (wk 3-on)
Side-to-side bounding	Wk 2, 4-on	10 s (wk 1), 20 s (wk 2), 30 s (wk 3-on)
Single-leg hop, hop, stick landing	Wk 2-on	5 reps each leg
Jump, jump, jump, vertical jump	Wk 2	NA
Single-leg jump	Wk 3-on	5 reps each leg
Jump into bounding	Wk 3	4 lengths basketball court
Diagonal bounding	Wk 3-on	2 lengths basketball court
Agility runs		
Shuttle runs	All	10 reps
Between 2 rows of 5 cones; rows 15-m apart		
Sprint to cone, backward jog to next cone		
Diagonal runs	All	10 reps
Between 2 rows of 5 cones; rows 15-m apart		
Sprint to cone, sprint to next cone		
Lateral shuffles	All	10 reps
Between 2 rows of 5 cones; rows 4.6-m apart, side shuffle from cone to cone		

trained athletes compared with the 370 control subjects (0.10 and 0.49 per 1000 AE, respectively, $P = 0.04$). This was the first level I study known to be performed in a mixed-ethnicity, predominantly low-income urban population. One problem was that only 37% of invited coaches participated in the study. Eligible coaches who did not enroll cited reasons such as lack of time or interest or the inability to collect athletic exposure and injury data. In addition, coaches who did participate in the intervention did not use all of the prescribed exercises.

20.2.3 Walden

Walden et al. [17] tested the effectiveness of a 15 min neuromuscular program (Table 20.5) in 2479 adolescent soccer players followed over

Table 20.5 Walden [17]

Exercise	Instructions	Reps/duration
One-legged knee squat	Slow movement with smooth turn, horizontal pelvis and nonsupporting foot in front of the body with slightly flexed hip and knee	
Level A	Hands on hips	3 × 8–15 reps
Level B	Hold the ball over head with straight arms	3 × 8–15 reps
Level C	Hands on hips; mark with nonsupporting foot just above ground at 12-02-04-06 o'clock positions	3 × 5 reps
Level D	Bend down while holding the ball and let the ball touch the ground outside supporting foot; make diagonal movement upward and raise the ball over head with straight arms on contralateral side	3 × 8–15 reps
Pair exercise	Teammate stands slightly oblique in front of you, and the ball is pressed between lateral sides of feet of nonsupporting legs	3 × 5–10 reps
Pelvic lift	Supine position; lift pelvis from the ground while keeping back straight	
Level A	Both feet on the ground and hands across the chest	3 × 8–15 reps
Level B	One foot on the ground and contralateral leg flexed in the hip and knee 90° with both hands on the knee	3 × 8–15 reps
Level C	One foot on football and contralateral leg flexed in the hip and knee 90° with arms on the ground alongside the body	3 × 8–15 reps
Level D	One foot on the ground and the other in the air; keep the upper arms on the ground with elbows flexed 90°; push away supporting foot and land on contralateral foot	3 × 8–15 reps
Pair exercise	Teammate stands with flexed knees and supports heel of one of your feet in her hands; hands across the chest and lift pelvis	3 × 8–15 reps
Two-leg knee squat	Slow movement with smooth turn, back in straight position and feet shoulder-wide apart with soles in contact with the ground	3 × 8–15 reps
Level A	Hold the ball in front of the body with straight arms	3 × 8–15 reps
Level B	Hands on hips	3 × 8–15 reps
Level C	Hold the ball over head with straight arms	3 × 8–15 reps
Level D	Same as level C but continue movement and rise up on toes after returning to starting position and stay briefly in that position	3 × 8–15 reps
Pair exercise	Teammate stands next to you approximately 1 m away, facing opposite directions; hold the ball between you with one hand and other hand on the hip; apply slight pressure on the ball while performing knee squat	3 × 8–15 reps
The bench	Lift body and keep it in straight line	
Level A	Prone position; support on knees and on lower arms with elbows kept under shoulders	15–30 s
Level B	Same as level A but with support on tip of feet	15–30 s
Level C	Same as level B but move foot to side and back to starting position; alternate sides	15–30 s
Level D	Lie sideways with support on foot and lower arm with elbow kept under shoulder and other hand on hip; lift hip off ground and stay briefly in that position with good control before slowly returning to starting position	5–10 reps
Pair exercise	Teammate stands behind you and holds your feet or lower legs; lift the body and walk forward by using hands on ground	15–30 s
The lunge	Take deep step with marked knee lift and soft landing; rear knee should not touch ground	
Level A	Hands on hips; move forward with each step	3 × 8–15 reps
Level B	Hold ball in front of body with straight arms; rotate upper body while stepping forward and position ball laterally of front leg; move forward with each step and alternate sides	3 × 8–15 reps
Level C	Hold ball over head with straight arms; perform forward lunge and push back with front leg and return to starting position	3 × 8–15 reps
Level D	Hold ball in front of body with straight arms; perform sideways lunge and return to starting position	3 × 8–15 reps

(continued)

Table 20.5 (continued)

Exercise	Instructions	Reps/duration
Pair exercise	Teammate stands in front of you 5–10 m away; perform forward lunge while making throw-in with ball	3 × 8–15 reps
Jump/landing	Make jump with soft landing; stay briefly in landing position	
Level A	Stand on one leg with knee slightly bent and hands on hips; make short forward jump and land on same foot; jump backwards to starting position	3 × 8–15 reps
Level B	Stand on two legs shoulder-wide apart with hands on back; make sideways jump and land on one foot; alternate sides	3 × 8–15 reps
Level C	Take a few quick steps on same spot and make short jump straight forward landing on one foot	3 × 5 reps
Level D	Same as level C but change direction and jump to one side (90° turn); alternate sides	3 × 5 reps
Pair exercise	Teammate stands in front of you approximately 5 m away; make two-leg jump while heading football and land on two legs	3 × 8–15 reps

one season. Compared with 2085 control players, there was no significant reduction in the noncontact complete ACL injury rate. The number of AE for both groups was not provided.

The effect of this program on balance, vertical jump height, single-leg hop, sprint speed, and agility was studied in 52 players (28 trained and 24 control) [23]. After 11 weeks of training (two times per week), no significant improvements were found in any of the performance measures. Compliance with training was low, with mean player attendance reported as 59.6 ± 14.3%. The authors cited limitations of training dosage and low-intensity exercises as potential reasons for the poor results.

20.2.4 HarmoKnee

Kiani et al. [6] assessed the effect of the HarmoKnee program in 777 high school soccer players. Training was performed two times per week before the season began and then one time per week during the season (Table 20.6). There was no significant difference in the noncontact injury rate between these players and 729 control players.

20.2.5 The "11"

Steffen et al. [15] developed an intervention warm-up program termed the "11" in female soccer players (Table 20.7). Participants in the Under-17 league system in Norway were randomized to either the intervention group (1073 players) or control group (947 players). Training was done every practice for 15 consecutive sessions and 1×/week thereafter for the remainder of the season. There was no significant difference between groups in the incidence of noncontact ACL ruptures. The authors cited the most likely explanation for the study's results was poor compliance, as the intervention teams only participated in 60% of the available training sessions during the first half of the season and in 44% during the second half.

Steffen et al. [21] in a separate investigation examined the effects of the "11" program on athletic performance indicators in 18 high school female soccer players. Training was conducted 3×/week for 10 weeks. The authors reported that there were no significant improvements in lower extremity or hip strength, vertical jump height, speed on a 40-m run, accuracy in two sports performance tests, or knee valgus angle on two jump tests.

Table 20.6 HarmoKnee [6]

Exercise	Duration
Warm-up: during each of these exercises, we encouraged straight alignment hip-knee-foot; low center of gravity; lightly flexed knees; and soft and controlled landing. Optionally, ball and passing drills can be introduced where appropriate	≤10 min
Jogging	≥4–6 min
Backward jogging on the toes	~1 min
High-knee skipping: skip with an exaggerated motion by driving the left knee and the right arm toward the sky. Soft landing on the right foot. The sequence is repeated using the opposite leg and arm. No need to jump high or long	~30 s
Defensive pressure technique: sliding slowly, zigzag backward	~30 s
One and one: alternating forward zigzag running and pressure technique zigzag backward	≥2 min
Muscle activation: during each of these exercises, we encouraged carefully holding and contracting the muscle for approximately 4 s, focusing on "finding" your muscles. We recommend stretching only in cases of limited range of motion; stretching is not recommended for players with joint laxity	~2 min
Activation of calf muscles	4 s for each side/leg
Activation of quadriceps muscles	4 s for each side/leg
Activation of hamstring muscles	4 s for each side/leg
Activation of hip flexor muscles	4 s for each side/leg
Activation of groin muscles	4 s for each side/leg
Activation of hip and lower back muscles	4 s
Balance: proper landing and takeoff in a jump is the most important movement in this exercise. We encouraged straight line hip-knee-foot; standing with feet shoulder-width apart; soft and controlled landing with flexed knees; freezing the landing before taking off again; and keeping a low body-center of gravity. Contract and hold stomach and buttocks during the whole exercise. Perform exercises slowly; no need to jump high.	~2 min
Forward and backward double-leg jumps	~30 s
Lateral single-leg jumps	~30 s
Forward and backward single-leg jumps	~30 s
Double-leg jump with or without the ball (optional)	~30 s
Strength: we encouraged soft and controlled landing, contracting stomach and buttocks, straight line hip-knee-foot	~4 min
Walking lunges in place	~1 min
Hamstring curl (in pairs)	~1 min
Single-knee squat with toe raises	~1 min
Core stability: we encouraged contracting stomach and buttocks; straight line through the body; if there is back pain, stop or modify the exercise (do not hold your breath)	~3 min
Sit-ups	~1 min
Plank on elbows and toes	~1 min
Bridging	~1 min

Steib et al. [22] reported significant improvements in reach distances on the star excursion balance test in 21 adult handball players following 11 weeks of training. Slight modifications were made to the "11" program for these handball athletes. Compared with a control group of 20 players, significant improvements in anterior, posterior, medial, and lateral directions and the total score were noted after 6 weeks of training; the improvements contin-

Table 20.7 The "11" [15]

Exercises	Description	Duration
Core stability		
The bench	Leaning on elbows in the prone position, lift the upper body, hips, and knees so that the body forms a straight line from the shoulder to the heels. Hold this position	15 s × 4 reps
Sideways bench	Leaning on 1 elbow in the side position, lift top leg and hips until the shoulder, hip, and top leg are in straight line and parallel to the ground. Hold this position	15 s × 2 reps on each side
Balance		
Cross-country skiing	In single-leg stance, continuously bend and extend the knee of the supporting leg and swing the arms in rhythm	15 s × 2 reps on each leg
Chest pass in single-leg stance	Partner exercise with both players in single-leg stance. Throw a ball back and forth	15 s × 3 reps on each leg
Forward bend in single-leg stance	Same as above, but before throwing the ball back, touch the ball to the ground without putting weight on it	15 s × 3 reps on each leg
Figure of eights in single-leg stance	Same as above, but before throwing the ball back, move the ball in a figure eight through and around both legs	15 s × 3 reps on each leg
Plyometrics		
Line jumps (sideways, forward-backward)	2-leg jumps sideways over a line and forward-back as quickly as possible	15 jumps each type
Zigzag shuffle (forward-backward)	Shuffle sideways with a low center of mass to the first cone, turn so that the other shoulder points to the next cone, and complete the zigzag course as fast as possible	2 reps each direction (20 m)
Bounding	Spring as high and far as possible off the supporting leg. Bring the knee of the trailing leg up as high as possible and the opposite arm in front of the body. Continuous bounding, switching legs on each takeoff.	10–15 jumps × 3 reps (20 m)
Strength		
Nordic hamstrings	Lower legs are held stable by a partner. Slowly lean forward keeping the upper body and hips straight while resisting the forward-falling motion by the hamstrings muscles	5 reps

ued until the study period concluded. There were no improvements found in static balance (single-leg balance center of pressure).

20.2.6 Pasanen

Pasanen et al. [10] developed an ACL intervention warm-up program for female floorball players (Table 20.8). Elite-level adult players in Finland trained one to three times per week for 20–30 min during practice for one season. There was no significant difference in the incidence of ACL injuries between the 256 trained and 201 control players (0.09 and 0.05 per 1000 AE, respectively). The study lacked the appropriate statistical power in regard to the number of noncontact ACL injuries (three in each group). There was a significant reduction in noncontact leg injuries overall ($P < 0.001$) in the intervention group, with the greatest effects observed in ankle ligament injuries. The authors concluded that the training was effective and should be included in the weekly training or teams and that training should be considered in children no older than age 12 as greater improvements in motor technique and skills would be expected in younger athletes.

Table 20.8 Pasanen [10]

Exercise	Duration
Running (5–7 min)	1–2 reps each, 20 m
Carioca running	
Sideways gallop	
Zigzag running forward	
Zigzag running backward	
Skipping	
Walking lunges × 4–8 steps and slow forward running	
Slow alternate bounding	
Combination hops (right-right-left-left-right-right)	
Balance (1 of 3 exercises, 5–7 min)	
Squat technique with stick (either double- or single-leg)	
Double-leg	2–3 × 10–15 reps
Single-leg	2–3 × 8–10 reps each leg
Balance exercise with medicine ball	
Single-leg	2–3 × 4–6 throws each leg
Balance board exercise (either double- or single-leg)	
Double-leg: with or without stick or ball	2–3 × 20–30 s
Single-leg: with or without stick or ball	2–3 × 20–30 s each leg
Plyometrics (5–7 min)	
Forward jumps (double- or single-leg)	
Double-leg jumps	2–3 × 3–5 reps
Single-leg hops	2–3 × 3–5 reps each leg
Jumps in place	
3 alternative exercises (lateral skate leap, split squat jump, cycled split squat jump)	2–3 × 8–12 reps
Jumps over stick or sticks (double- or single-leg)	
Double-leg	
3 alternative exercises (backward and forward jumps, lateral jumps, or 3-dimensional jumps)	2–3 × 8–12 reps
Single leg	
3 alternative exercises (backward and forward hops, lateral hops, or 3-dimensional hops)	2–3 × 4–8 reps each leg
Strengthening (1 exercise for lower legs, 1 for core, 5–7 min)	
Double-leg squat with partner on back	2–3 × 8–12 reps
Single-leg split squat	2–3 × 4–8 reps each leg
Nordic hamstrings	2–3 × 4–8 reps
Isometric side and front bridge	2–3 × 10–30 s each side
Cross curl up	2–3 × 10–20 reps each side
Flexibility (for players with limits on low back function and flexibility, 5 min)	
Seated hip and low back neutral zone	2–3 × 20 s
Hamstring strength	1–2 × 20 s each side
Kneeling hip flexor stretch	1–2 × 20 s each side

m meters, *reps* repetitions, *s* seconds

20.2.7 Knee Ligament Injury Prevention (KLIP)

Pfeiffer et al. [12] developed the knee ligament injury prevention (KLIP) program which was tested in high school female basketball, soccer, and volleyball athletes. The program was performed two times per week for approximately 20 min throughout one season at either the beginning or end of practice (Table 20.9). There was no significant difference in the incidence of noncontact ACL injuries between 862 trained athletes and 577 control athletes (0.17 and 0.08 per 1000 AE, respectively). The odds of injury were equivalent for the two groups (odds ratio = 2.05; 95% confidence interval, 0.21–21.7). The study was not randomized and lacked the appropriate statistical power in regard to the number of noncontact ACL injuries. The authors indicated that they had initially selected a randomized study design but that many of the school administrators and coaches were not willing to participate in such a study. Problems were also cited with coaches unwilling to modify their practices to include ACL intervention training.

Irmischer et al. [5] studied the effectiveness of the KLIP program in 14 collegiate students in reducing ground reaction forces from a drop-jump and improving vertical jump height. The subjects trained two times per week for 9 weeks. The authors reported a significant decrease after training in peak vertical impact forces (5.3 ± 1.0 body weight [bw] to 3.9 ± 0.6 bw, $P = 0.0004$) and rate of force development (0.11 ± 0.03 bw/ms and 0.08 + 0.02 bw/ms, $P = 0.02$) on landing from a drop-jump. There was no significant increase in vertical jump height.

Table 20.9 Knee ligament injury prevention (KLIP)[a] [12]

Phase	Week	Component
1	1, 2	Straight jumps, tuck jumps, standing broad jump, bound in place
2	3, 4	Straight jumps, tuck jumps, 180° jumps, double-leg jumps, single-leg lateral jumps, 45° lateral leaps
3	5, 6	Tuck jumps, single-leg lateral leaps, single-leg forward hops, combination jumps, 180° jumps, 45° lateral leaps
4	7 to end of season	Straight jumps, single-leg forward hops × 3, combination jumps, 180° jumps, standing broad jumps, single-leg 45° lateral hops

[a] Additional agility drills done after the jump program include stop and go, "W" drill, figure of eights, and left/right cuts

20.2.8 Petersen

Petersen et al. [11] conducted a study of a warm-up ACL intervention program in female team handball players of varying levels in Germany. The program, comprised of balance board and plyometric exercises (Table 20.10), was con-

Table 20.10 Petersen [11]

Phase	Balance board exercises	Jump exercises
I	Single-leg stand combined with handball-specific throwing exercises	Vertical, forward, backward, and side-to-side jumps on the floor
II	Round soft balance board (both and single-leg stand) and simple throwing exercises with partner	Vertical, forward, backward, and side-to-side jumps on smooth mat
III	Round soft balance board and rectangular balance board (single-leg stand) and simple throwing exercises with partner	Forward jump from box to a hard mat and forward jump from hard mat to box
IV	Round soft balance board and rectangular balance board (single-leg stand) and complex throwing exercises to the goal (5 s balancing and throw to the goal)	Forward jump from floor to smooth mat with throwing exercises, then side-to-side jumps on smooth mat
V	Round hard balance board and rectangular balance board (single-leg stand) and complex throwing exercises with closed eyes (5 s balancing and throw to the goal)	Forward jump from box to smooth mat, with throwing exercises then side-to-side jumps on smooth mat
VI	Round soft balance board and rectangular balance board (single-leg stand) and complex throwing exercises to goal	Forward jump from box to smooth mat, with closed eyes then side-to-side jumps on smooth mat

ducted three times per week during the preseason for 8 weeks and then one time per week during the season. There was no significant difference in the ACL injury rate between the 134 athletes in the intervention group and the 142 players in the control group (0.04 and 0.21 per 1000 AE, respectively). The study was not randomized, and there was insufficient statistical power regarding the number of ACL injuries sustained to avoid a type II statistical error.

20.2.9 DiStefano

DiStefano and associates studied the effects of a general and a stratified ACL intervention training program (Table 20.11) on improving landing technique during a drop-jump test in 173 athletes aged 10–17 years [3]. One group underwent a “stratified” training program that was designed according to specific movement errors detected on a double-leg squat test at baseline (medial knee displacement, toe out, or neutral), and another group participated in a generalized program where all performed the same exercises regardless of movement errors detected before training. All training was accomplished within 10–15 min at the start of every soccer practice three to four times per week.

Changes in landing technique were assessed using the Landing Error Scoring System (LESS). The LESS rates nine jump-land characteristics, with a higher score indicating a greater number of landing errors and a poor technique. The training groups were classified according to gender and age as either pre-high school (aged 10–13 years) or high school (14–17 years). The main findings were that subjects with the poorest LESS scores had the greatest improvements in landing technique and that the high school-aged athletes improved their landing technique more than pre-high school-aged subjects. There was no difference in changes in landing technique between the stratified and generalized programs or between males and females. The authors concluded that high school-aged athletes were a primary target population for training and that a “one-size-fits-all” training program was effective in improving landing techniques in both male and female athletes.

The general and stratified ACL intervention training programs were analyzed in a separate study in regard to retention of improvements in LESS scores [26]. A total of 140 soccer players aged 11–17 years underwent training for

Table 20.11 DiStefano [3]

Exercise	General program	Stratified program[a]
Strength	Walking lunge	Medial knee displacement: side bridge hip raise Toe out: heel raise with internal rotation Neutral alignment: side-step tubing, hip bridge, diagonal ball reach All: multiplanar lunges, single-leg squat
Plyometrics	Forward line hops Sideways line hops Vertical jump with header	All: multiplanar hops to balance Forward line hops Sideways line hops Squat jumps
Balance	Single-leg balance toss	NA
Agility	Sideways shuffle	NA
Flexibility	Adductor stretch Hamstring stretch Quadriceps stretch Hip flexor stretch Calf stretch	Medial knee displacement: adductor stretch Toe out: calf stretch

NA not applicable

[a] Subjects performed exercises according to performance on a double-leg squat test, classified as either medial knee displacement, toe out, or neutral

either 3 months (short duration) or 9 months (extended duration) before each practice. The LESS was conducted before training began, within 1 week of the end of the training period, and then 3 months later. While both the short and extended duration subgroups demonstrated significant improvements initially, only the extended duration trained group retained these improvements.

20.2.10 The "11+"

In an effort to improve the results of the "11" training program, a modified intervention was developed and described by Soligard et al. [14] (Table 20.12). A total of 125 soccer clubs in Norway participated for one season (8 months). There was no significant difference in the rate of acute noncontact injuries between the 1055

Table 20.12 The "11+" [14]

Exercise	Duration
1. Running, 8 min (1 rep = 6–10 pairs parallel cones)	2 reps each
Straight ahead	
Hip out	
Hip in	
Circling	
Running and jumping	
Running, quick run	
2. Strength, plyometrics, balance, 10 min (1 of 3 levels each session)	
Plank:	
Level 1: both legs	3 × 20–30 s
Level 2: alternate legs	3 × 20–30 s
Level 3: one leg lift	3 × 20–30 s
Side plank:	
Level 1: static	3 × 20–30 s (each side)
Level 2: dynamic	3 × 20–30 s (each side)
Level 3: with leg lift	3 × 20–30 s (each side)
Nordic hamstring lower:	
Level 1	3–5 reps
Level 2	7–10 reps
Level 3	12–15 reps
Single-leg balance	
Level 1: holding the ball	2 × 30 s (each leg)
Level 2: throwing the ball with partner	2 × 30 s (each leg)
Level 3: testing partner	2 × 30 s (each leg)
Squats	
Level 1: with heels raised	2 × 30 s
Level 2: walking lunges	2 × 30 s
Level 3: single-leg squats	2 × 10 (each leg)
Jumping	
Level 1: vertical jumps	2 × 30 s
Level 2: lateral jumps	2 × 30 s
Level 3: box jumps	2 × 30 s
3. Running, 2 min	2 reps each
Running over pitch	
Bounding run	
Running and cutting	

reps repetitions, *s* seconds

trained players and the 837 control players. The incidence of ACL injuries was not provided. The intervention group did have a reduced incidence of injuries overall, overuse injuries, and severe injuries. The authors concluded that the program was effective and that young children should initiate this type of training as soon as they begin participating in organized soccer.

20.2.11 Kerlan-Jobe Orthopedic Clinic Modified Neuromuscular Training Program

Chappell and Limpisvasti [2] investigated the effects of a warm-up program in 30 female collegiate basketball and soccer players. Training was accomplished for 10–15 min before every practice 6 days a week for 6 weeks (Table 20.13). Knee kinematics and kinetics were assessed using drop-jump and stop-jump tasks, and performance was measured with a vertical jump and a timed single-leg hop test. After training, significant increases were noted in knee flexion angle at foot strike ($P = 0.003$) and maximum knee flexion angle during stance phase ($P = 0.006$). Significant decreases were noted for hip flexion at foot strike ($P = 0.05$), maximum hip external rotation ($P = 0.02$), maximum knee flexion moment ($P = 0.04$), and maximum dynamic knee valgus ($P = 0.04$). Vertical jump height increased ($P < 0.001$) and times for the single-leg hop improved for both legs ($P \leq 0.001$). The authors concluded that the program improved some motor control strategies in select jumping tasks in collegiate female athletes and suggested that training should be performed in younger subjects in whom modification of these movement patterns may show an even greater effect.

Table 20.13 Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Training Program [2]

Exercise	Duration
Abdominal crunches	20 reps
Cross crunches	20 reps
The plank	60 s
Lunges	20 reps
Single-leg chest pass	20 each side
Single-leg forward-bend pass	20 each side
Single-leg figure of eight	20 each leg
Line jumps	20 reps
Lateral shuffle	20 each side
Bounding	20 reps

reps repetitions, *s* seconds

20.2.12 Myklebust

Myklebust et al. [9] designed a 3-part program comprised of balance, plyometric, and agility exercises for female team handball players (Table 20.14). The program, supervised by phys-

Table 20.14 Myklebust [9]

Floor exercises
Week 1: Running and planting with partner running backward and giving feedback on the quality of the movement. Change position after 20 s
Week 2: Jumping exercise: right leg-right leg over to left leg-left leg and finishing with a 2-ft landing with flexion in both hips and knees
Week 3: Running and planting (as in week 1) with full plant and cut movement with ball, focusing on knee position
Week 4: 2 and 2 players together, 2-leg jump forward and backward, 180° turn and the same movement backward; partner tries to push the player out of control, focus on landing technique
Week 5: Expand movement from week 3 to full plant and cut, and then a jump shot with 2-legged landing
Mat exercises
Week 1: 2 players, standing on 1 leg on the mat throwing to each other
Week 2: Jump shot from a box (30–40 cm high) with a 2-foot landing with flexion in the hip and knees
Week 3: “Step” down from box with 1-leg landing with flexion in hip and knee
Week 4: 2 players both standing on balance mats trying to push partner out of balance, first on 2 legs and then on 1 leg
Week 5: Players jump on a mat catching a ball, then take a 180° turn on mat
Wobble board exercises
Week 1: 2 players standing 2-legged on board throwing to each other
Week 2: Squats on 2 legs, then on 1 leg
Week 3: 2 players throwing to each other, 1 foot on the board
Week 4: One foot on the board, bounding the ball with eyes shut
Week 5: 2 players, both standing on balance boards trying to push partner out of balance, first on 2 legs and then on 1 leg

ical therapists, was performed three times per week for 5–7 weeks before the start of the season and then one time per week during the season. There were 942 athletes in the control group (1998–1999 season) and 1705 in the intervention group (2 seasons: 1999–2001) from the top 3 divisions of the Norwegian Handball Federation. Compliance with the program, defined as attendance of >15 training sessions and 75% player participation, was only fulfilled in 26% of the teams in the first intervention season and in 42% of the teams in the second season.

In a subgroup of elite division athletes, the risk of ACL injury was reduced in those who completed the training program compared to those who did not; however, the ACL incidence rates per AE were not provided. The study was not randomized, the ACL injuries were not sorted according to contact versus noncontact mechanisms, and there was insufficient statistical power regarding the number of ACL injuries sustained to avoid a type II statistical error. The authors concluded that a preventative program most likely works best in highly motivated, elite athletes.

Holm et al. [4] conducted an investigation regarding the effectiveness of this program in improving static and dynamic balance, proprioception, strength, and single-leg hop test performance in 27 elite team handball players. There was a significant improvement in two-leg dynamic balance assessed using a KAT 2000 (OEM Medical, Carlsbad, CA) moveable platform device (balance index score, 924 ± 225 versus 778 ± 714, $P = 0.003$). However, there were no significant increases in single-leg static balance, proprioception, isokinetic lower extremity muscle strength, or distance hopped on single-leg function tests.

20.2.13 Warm-Up for Injury Prevention and Performance (WIPP)

The Warm-up for Injury Prevention and Performance (WIPP) is a program designed to be performed after athletes or teams have completed a 6-week course of Sportsmetrics. WIPP incorporates the essential components of Sportsmetrics and a final agility component and is 20 min in duration (Table 20.15). We stress that WIPP was not designed to be used alone for knee ligament injury prevention training but replaces the regular warm-up of a team or athlete who have already completed Sportsmetrics.

Table 20.15 Warm-up for Injury Prevention and Performance (WIPP)

Exercise	Duration
Dynamic warm-up:	
Straight leg march	20 s each exercise
Hand walk	
Leg cradle walk	
Hip rotatory walk	
Jump training:	
Tuck jump	30 s
Squat jump	30 s
180° jump	30 s
Scissor jump	30 s
Side-to-side barrier hop	15 s each leg
Strength training:	
Steamboats, single-leg	30 s each leg
Lateral step, single-leg	20 s each leg
Supine hamstring, single-leg	30 s each leg
Abdominal crunch	60 s
Modified plank	60 s
Flexibility:	
Hamstring	20 s each side
Hip flexor	
Quadriceps	
Gastrocnemius	
Dynamic warm-up:	
Quick feet	30 s each direction
Nebraska drill	30 s each run

s seconds

Critical Points

- ACL intervention warm-up programs:
  - Prevent Injury and Enhance Performance (PEP)
  - Knee Injury Prevention Program (KIPP)
  - Walden
  - HarmoKnee
  - The “11”
  - Pasanen
  - Knee ligament injury prevention (KLIP)
  - Petersen
  - DiStefano

- The “11+”
- Kerlan-Jobe Orthopedic Clinic Modified Neuromuscular Training Program
- Myklebust
- Warm-up for Injury Prevention and Performance (WIPP) Program

20.3 Overall Outcomes of Warm-Up Programs

20.3.1 Compliance with Training

One of the major potential advantages of ACL intervention warm-up programs cited by investigators is high player compliance with training. Unfortunately, this review detected inconsistency with compliance rates among the studies published to date [6, 10, 15]. Investigations that reported poor compliance rates listed a variety of reasons such as player boredom, long seasons, poor attitudes among coaches and school administration regarding the necessity for injury prevention training, lack of supervision, lower player skill level, limited practice time during the season, and a short preseason. There are many factors associated with player compliance, and this review demonstrates that simply designing a program that is brief in duration and easy for the athletes to perform may not result in the desired effects. Alterations in the program and a gradual increase in intensity and difficulty of the exercises may be beneficial in increasing compliance and player effort.

20.3.2 Effect on ACL Injury Rate

Only two programs (PEP [8] and KIPP [18]) had a statistically significant effect in reducing the ACL injury incidence rate. There were study design flaws in nearly all of the investigations, with the most common being a lack of randomization and an insufficient number of ACL ruptures to avoid a type II statistical error. Future studies will require greater numbers of players, hours of exposure, and noncontact ACL injuries in order to determine the impact of warm-up programs on reduction of knee ligament injuries.

20.3.3 Effect on Athletic Performance Indices

Overall, few improvements were noted, and it is difficult to assimilate the effects of the training programs alone on these factors because five studies conducted the investigation during the course of an athletic season without a control group. Two studies showed improved hip and knee strength following PEP training [7, 20]. Only one study demonstrated increased vertical jump height (mean, 3.7 cm) [2]. None of the programs resulted in improved sprint speed or agility.

20.3.4 Effect on Neuromuscular Indices

Seven studies investigated the effect of ACL intervention warm-up training programs on neuromuscular indices with inconclusive results reported. Changes in knee kinematics and kinetics on a drop-jump task were presented in four studies. Other tasks including a vertical jump, rebound jump, and stop jump were assessed in just one study each. Differences in the tasks selected to assess changes in neuromuscular indices, kinematic and kinetic factors analyzed, subject ages, frequency and duration of training programs, and training components preclude comparisons between programs. Some programs had a positive effect on improving lower extremity landing factors considered to be problematic in terms of ACL injury risk [3, 5], while others had no such effect [20, 21]. Other programs had mixed results, and their ability to improve neuromuscular indices remains unclear [2, 7, 13].

20.3.5 Effect of Program Components

Most of the warm-up programs adopted a multifaceted approach in the selection of exercise components. Myklebust et al. [9] included agility, balance, awareness of vulnerable knee positions, and playing technique and indicated it was not possible to determine which part of the program may be effective in helping reduce ACL injuries in elite female handball players. Petersen et al. [11] integrated balance, plyometric, and handball-specific throwing exercises in a circuit training format. Their program was designed in part from demands of coaches who wanted the program to include handball-specific functional activities and be short in duration in order not to take time away from practice.

Pfeiffer et al. [12] believed that the absence of strength training may have played a role in the lack of a training effect of their KLIP program on the ACL injury rate. Steffen et al. [15] hypothesized that the "11" program was ineffective in part due to the lack of variation and progression of exercises throughout the season. The same ten exercises were during every practice session, and the authors believed this resulted in reduced motivation among coaches and players. The proposal was also advanced that more dynamic exercises that better resembled female soccer competition may be beneficial, such as running with rapid changes of direction, dribbling, and landing after heading and perturbations.

The PEP program developed techniques to reduce friction using a three-step deceleration technique; emphasized proper landing technique by promoting knee and hip flexion and avoiding excessive valgus knee position on landing and lateral maneuvers; and included exercises to improve strength in the hamstrings, gluteus medius, and hip abductors [8]. The authors acknowledged that the program may require repeated use over several weeks for athletes to demonstrate changes in strength, balance, and proprioception.

It is evident that much work remains to be done in terms of ACL intervention warm-up programs in order to improve player compliance and reduce injury rates. One of the most concerning findings of this review was that only two programs had a statistically significant effect in reducing ACL injury rates. We believe that a preseason intervention training program that is longer in duration in terms of each session and promotes greater improvements in strength, landing and cutting techniques, agility, and flexibility may be required first. Then, athletes may participate in a shorter ACL injury prevention warm-up program throughout the season that incorporates the essential components of the longer intervention already completed, including continued emphasis on proper technique and avoidance of potential high-risk injury situations. In addition, in order for warm-up ACL intervention programs to reach maximum effectiveness, the authors believe that coaches must adopt a crucial role and insist that athletes complete the entire warm-up program during every practice session.

Critical Points Compliance rates with training inconsistent:

- – Player boredom
- – Long seasons
- – Poor attitudes among coaches and school administrators on necessity for injury prevention training
- – Lack of supervision
- – Lower player skill level
- – Limited practice time during the season
- – Short preseason

- PEP and KIPP significantly reduced ACL injury incidence rate.
- Study design flaws common.
- Few improvements in athletic performance tests.
- Mixed results in changes in neuromuscular indices.
- Most programs multifaceted in exercise components.

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21

Effect of Intervention Programs on Reducing the Incidence of ACL Injuries, Improving Neuromuscular Deficiencies, and Enhancing Athletic Performance

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Abstract

This chapter reviews the current available data regarding the effectiveness of the ACL intervention programs in reducing injury rates, improving knee kinematic and kinetic factors, and enhancing athletic performance indicators. Three programs published to date that reported ACL injury rates in female athletes according to athlete exposures statistically reduced the injury rate. A multitude of studies have analyzed the effectiveness of knee injury prevention programs in changing kinematic or kinetic factors in female athletes. However, the effectiveness of these programs in altering neuromuscular indices under reactive, unplanned, actual athletic conditions remains largely unknown. While many studies have documented changes in athletic performance indicators following ACL injury prevention training in female athletes, the results remain mixed.

21.1 Introduction

Since the first publications of knee ligament injury prevention, training programs appeared in the sports medicine literature for skiing in 1995 [1] and female high school athletes in 1996 [2]; at least 30 intervention programs have been published that focused on female athletes (Table 21.1). Multiple investigations have been conducted to determine the effectiveness of these programs in reducing anterior cruciate ligament (ACL) injury rates [7, 18, 20, 25, 26, 31, 32, 34, 35, 39], improving knee kinematic and kinetic factors [2, 4, 5, 8–12, 15, 17, 19, 21, 22, 24, 29, 42–45, 48–57, 59, 61–63, 65, 67–75], enhancing strength or other athletic performance indicators [3, 5, 8, 10–15, 17, 19, 22–24, 29, 38, 42, 45, 48–51, 53, 54, 56–58, 61–63, 66, 67, 76, 77], and improving static and dynamic balance [13, 16, 29, 40, 47, 60, 64, 66].

There exist differences in opinion regarding the frequency, intensity, duration, and components that should comprise an ACL intervention training program. One issue is if a significant reduction in the injury rate can be accomplished with “warm-up programs” that are relatively short in session duration (10–20 min), but long in total training duration (for instance, one season). This is in contrast to preseason programs that last 6–8 weeks but require 60–90 min of training per session. A second issue is whether ACL intervention training should be modified according to the

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Table 21.1 Summary of published ACL injury prevention programs for female athletes

Program or author (citation)	Program duration	Program components	ACL injury rate calculated by exposure data?	Kinematic, kinetic, balance data?	Athletic performance test data?
Sportsmetrics [2–17]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility (Chap. 17) Volleyball, basketball, soccer, tennis-specific exercises added for agility, speed, and endurance (Chap. 18)	Yes	Yes	Yes
Prevent Injury and Enhance Performance Program (PEP) [18–23]	20-min warm-up in-season	Running, flexibility, strength, plyometrics, agility (Table 20.3)	Yes	Yes	Yes
Knee Ligament Injury Prevention Program (KLIP) [24, 25]	20-min warm-up, 2×/wk in-season	Plyometrics, agility (Table 20.7)	Yes	Yes	Yes
International Football Federation (FIFA) "11" [26];	20-min warm-up, 15 consecutive sessions, then 1×/wk in-season	Core, balance, plyometrics, strength (Table 20.5)	Yes	No	No
FIFA 11+ (also known as F-MARC 11+) [27, 28]	15-min warm-up, 3×/wk for 10wk in-season; 20-min warm-up, all practices in-season	Running, strength, plyometrics, balance (Table 20.10)	No	Yes	Yes
Myklebust [29, 30]	15-min warm-up, 3×/wk for 5–7 wk, then 1×/wk in-season	Floor, mat, wobble board (Table 20.9)	Yes	Yes	Yes
Petersen [31]	10-min warm-up, 3×/wk for 8 wk, then 1×/wk in-season	Balance, plyometrics (Table 20.8)	Yes	No	No
Pasanen [32, 33]	20–30-min warm-up, 2–3×/wk in-season	Running, balance, plyometrics, strength (Table 20.6)	Yes	No	Yes
Knee Injury Prevention Program (KIPP) [34]	20-min warm-up before practice in-season	Plyometrics, strength, agility (Table 20.14)	Yes	No	No
HarmoKnee [35]	20–25-min, 2 x/wk preseason, 1 x/wk in-season	Plyometrics, strength, core stability (Table 20.5)	Yes	No	No
Walden (Knäkontroll, SISU Idrottsböcker, Sweden) [36–39]	15-min warm-up, 2×/wk in-season	Plyometrics, strength	Yes	Yes	Yes
Myer [40–47]	90 min, 3×/wk for 6 wk	2 programs: plyometric or balance and dynamic stabilization	No	Yes	Yes

Table 21.1 (continued)

Program or author (citation)	Program duration	Program components	ACL injury rate calculated by exposure data?	Kinematic, kinetic, balance data?	Athletic performance test data?
Lephart [48]	30 min, 3×/wk for 8 wk	2 programs: plyometric (flexibility, balance, strength, agility), basic (flexibility, balance, strength)	No	Yes	Yes
Kerlan-Jobe [49]	10–15-min warm-up, 6×/wk for 6 wk in-season or preseason	Strength, balance, plyometrics (Table 20.12)	No	Yes	Yes
Herman [50, 51]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls Feedback in 1 group, 3 sessions, video landing technique analyzed	No No	Yes Yes	Yes Yes
Oslo Sports Trauma Research Center [52, 53]	20-min warm-up, 2×/wk for 18 wk in-season	Balance, agility, plyometrics, strength	No	Yes	Yes
Herrington [54]	15 min, 3×/wk for 4 wk	Plyometrics	No	Yes	Yes
DiStefano [55]	10–15-min warm-up, 3–4×/wk in-season	2 programs: 1 general, 1 designed on performance on squat test (Table 20.13)	No	Yes	No
Sportsmetrics plyometrics only [56]	60 min, 3×/wk for 8 wk	Plyometrics	No	Yes	Yes
Functional Stabilization Training [57]	80 min, 3×/wk for 8 wk	Hip and core strengthening	No	Yes	Yes
Hurd [58]	60 min, 10 sessions over 3–4 wk	Perturbation on balance board, strength, agility	No	Yes	No
Kato [59]	20 min, 3×/wk for 4 wk during practice	Strength, plyometrics, balance	No	Yes	No
McLeod [60]	90 min, 2×/wk for 6 wk in-season	Strength, plyometrics, agility, balance	No	Yes	No
Wilderman [61]	15 min, 4 x/wk for 6 wk in-season	Agility drills	No	Yes	No
Nagano [62]	20 min, 3×/wk for 5 wk	Plyometrics, balance	No	Yes	No
Pfile [63]	20 min, 3×/wk for 4 wk	Plyometrics or core stability exercises	No	Yes	No
Steib [64]	15-min warm-up, 3×/wk for 11 wk	Strength, balance, plyometrics	No	Yes	No
Weltin [65]	20–40 min, 3×/wk for 4 wk in-season	Plyometrics only or plyometrics and lateral reactive jumps with perturbation	No	Yes	No
Hopper [66]	60 min, 3×/wk for 6 wk during season	Plyometrics, resistance strength	No	Yes	No

(continued)

Table 21.1 (continued)

Program or author (citation)	Program duration	Program components	ACL injury rate calculated by exposure data?	Kinematic, kinetic, balance data?	Athletic performance test data?
Letafatkar [67]	60 min, 3×/wk for 6 wk	Perturbation drills	No	Yes	No
Ericksen [68]	15 min, 3×/wk for 4 wk	Plyometrics	No	Yes	No
Brown [69]	3 different programs, 20–60 min 3×/wk for 6 wk	Sportsmetrics, plyometrics only, or core stability/balance only	No	Yes	No
Stearns [70]	30 min, 3×/wk for 4 wk	Plyometrics, balance	No	Yes	No

athlete's age and sport. Can a program that is successful in adolescent soccer players has similar outcomes in adult handball players? A third issue is whether athletes identified as having a high risk of sustaining a noncontact ACL injury should undergo a different training program than those who are believed to be at a lower risk for this injury. The difficulty with this issue is that there does not exist to date a comprehensive model that predicts ACL injury risk according to all of the potential risk factors: anatomical, environmental, hormonal, neuromuscular, familial, playing surface, equipment, cardiovascular conditioning, and nutrition.

Multiple meta-analyses [78–84] that assessed the ability of neuromuscular training programs to reduce ACL injury rates concluded that these intervention programs were indeed effective. However, these studies combined data from very different types of training programs and did not answer the major issues discussed above. Systematic reviews (that did not combine data of programs) have reported that, while some programs are effective, others do not significantly reduce the risk of ACL injury and stress the importance of understanding the variation in training protocols and study design in ascertaining the differences in outcomes [7, 85–87].

There are important qualifiers in the studies included in this chapter. First, nearly all of the investigations analyzed preplanned tasks in a controlled laboratory setting. The effectiveness of these types of programs in improving potentially deleterious neuromuscular indices under reactive, unplanned athletic conditions is unknown. Secondly, few studies provided effect sizes (ES) in addition to P values when reporting effects of training [10–12, 17, 61, 69]. The ES measures the magnitude of the effects of treatment and is especially relevant in studies with small sample sizes [88]. It is probable that some statistically significant findings ($P < 0.05$) reported in the studies in this chapter may have limited clinical relevance. A third qualifier is that few studies conducted a prospective power calculation of the sample size required to discern a detectable difference (95% CI) in knee and hip kinetic and kinematic factors resulting from the training program [4, 9, 11, 15, 19, 42, 44, 52, 68–70]. Finally, the determination of the magnitude of change required to actually reduce the risk of an ACL injury in knee and hip kinetic and kinematic factors remains unknown and is speculative at best.

The goals of this chapter are to review the current available data regarding the outcome of ACL intervention programs on the reduction of noncontact ACL injuries, improvement of neuromuscular deficiencies or at-risk body positions and movements, and enhancement of athletic performance indices in female athletes. This chapter serves to summarize the data, and the reader is referred to other chapters for further detail regarding these outcomes. Only programs that focused on adolescent or adult female athletes are included.

Critical Points

- More than 30 ACL intervention programs are published.
- Differences exist regarding frequency, intensity, duration, and components.
  - Effectiveness of warm-up programs
  - Modified according to age
  - Identification of at-risk athletes
- Chapter summarizes data on ability of programs to:
  - Reduce ACL noncontact injury rate
  - Improve neuromuscular deficiencies
  - Improve athletic performance indicators

21.2 Reducing the Incidence of Noncontact ACL Injuries

Ten intervention studies to date have reported noncontact ACL injury rates in female athletes according to athlete exposures (AE; Table 21.2) [7, 18, 20, 25, 26, 31, 32, 34, 35, 39]. Several other studies that reported data on intervention programs either did not provide ACL injury rates according to AE or did not indicate if the ACL injuries were noncontact in nature and are not included [1, 27, 30, 37, 89–92]. In addition, injury intervention studies that focused only on male athletes are not included in this review [88, 93, 94, 101].

Three programs—Sportsmetrics, Prevent Injury and Enhance Performance (PEP) program, and Knee Injury Prevention Program (KIPP)—statistically reduced the noncontact ACL injury rate [7, 20, 34]. Sportsmetrics was conducted in 700 high school female athletes before the start of the athletic season (see Chap. 17). The results from the trained athletes and 1120 control athletes demonstrated ACL injury rates of 0.03 and 0.21 per 1000 AE, respectively ($P = 0.03$). The PEP program was conducted in 1885 high school female soccer players over the course of one season (see also Chap. 20, Table 20.3) [20]. A significant reduction was reported in the noncontact ACL injury incident rate between the trained and 3818 control players (0.09 and 0.49 per 1000 AE, respectively, $P < 0.0001$). KIPP training was conducted in 485 high school female basketball and soccer players before practices over the course of one season (see also Chap. 20, Table 20.4) [34]. A significant decrease was found in the noncontact injury incident rate between the trained and 370 control players (0.10 and 0.48 per 1000 AE, respectively, $P = 0.04$).

Several studies [18, 25, 26, 30–32, 35, 39] reported that other intervention programs failed to have an effect on reducing ACL injury rates. Issues pertaining to poor compliance with training and a small number of noncontact ACL injuries were commonly cited as the reasons for the outcomes of these investigations. In general, ACL intervention programs published to date have had multiple methodological problems which preclude definitive answers regarding which programs are effective and which are ineffective. The lack of randomization and control, limited statistical power due to small number of exposures and ACL injuries, failure to determine ACL injury incidence according to AE, poor compliance with training, poor documentation of contact versus noncontact ACL injuries, and changes in study protocols over the course of investigations were found. Even with these acknowledged problems, recent conference and committee statements [95–97] have concluded that neuromuscular retraining can reduce the incidence of noncontact ACL injuries in female athletes. The International Olympic Committee current concepts statement [98] is shown below:

1. The program should include strength and power exercises, neuromuscular training, plyometrics and agility exercises.
2. Design as a regular warm-up program to increase adherence.
3. Focus should be on performance of the hip-knee-foot line and “kissing knees” should be avoided (excessive valgus strain).
4. Maintenance and compliance of prevention program before, during and after the sports participation season are essential to minimize injuries.
5. The drop vertical jump test should be used to identify players at risk.

Table 21.2 Effect of intervention programs on ACL noncontact injury rates in female athletes according to athlete exposures

Program or author (citation)	No. female athletes, sports	No. athlete exposures		No. ACL noncontact injuries (per 1000 athlete exposures)			Comments, study limitations
		Trained	Control	Trained	Control	*P* value	
Sportsmetrics [7]	700 trained, 1120 control High school team sports	36,724	61,244	1 (0.03)	13 (0.21)	0.03	Not randomized or double-blinded, low no. noncontact ACL injuries
KIPP [34]	485 trained, 370 control High school soccer, basketball	20,345	12,467	2 (0.10)	6 (0.48)	0.04	Injuries not sorted according to sport, only 37% of coaches invited participated
PEP [20]	1885 trained, 3818 control High school soccer	67,860	137,448	6 (0.09)	67 (0.49)	<0.0001	Not randomized
PEP [18]	583 trained, 852 control Collegiate soccer	35,220	52,919	2 (0.057)	10 (0.189)	NS	Low no. noncontact ACL injuries
Walden [39]	2479 trained, 2085 control Adolescent soccer	149,214	129,084	5 (0.03)	7 (0.05)	NS	Low attendance rates, low no. noncontact ACL injuries
HarmoKnee [35]	777 trained, 729 control High school soccer	66,981	66,505	0	5 (0.07)	NS	Not randomized, low no. noncontact ACL injuries
FIFA “11” [26]	1073 trained, 947 control High school soccer	66,423	65,725	3 (0.05)	2 (0.03)	NS	Poor compliance with training, low no. noncontact ACL injuries
Pasanen [32]	256 trained, 201 control Adult floorball	32,327	25,019	6 (0.18)	4 (0.16)	NS	Low no. noncontact ACL injuries
KLIP [25]	577 trained, 862 control High school soccer, basketball, volleyball	17,954	38,662	3 (0.17)	3 (0.08)	NS	Not randomized, low no. noncontact ACL injuries
Petersen [31]	134 trained, 142 control Team handball	NA	NA	0	5 (0.21)	NS	Not randomized, low no. noncontact ACL injuries

FIFA International Football Federation, *NS* not significant, *PEP* Prevent Injury and Enhance Performance Program, *KLIP* Knee Ligament Injury Prevention Program, and *KIPP* Knee Injury Prevention Program

Table 21.3 Effect of ACL intervention training on landing forces

Program or author (citation)	Subjects[a]	Tests	Landing forces
Sportsmetrics [2]	11 trained females, 9 control male High school volleyball	Vertical jump	Decreased landing forces mean 456 N ($P = 0.006$, ES = NA)
KLIP [24]	14 trained, 14 control College students	Step-land	Reduced peak vertical ground reaction forces from 5.3 ± 1.0 to 3.9 ± 0.6 BW ($P = 0.0004$, ES = NA), rate force development from 0.11 ± 0.03 to 0.08 ± 0.02 BW/meters per s ($P = 0.02$, ES = NA)
Herman [50]	29 trained strength, feedback 29 feedback only 18–30 y Recreational athletes	Stop-jump	All subjects combined decreased peak vertical ground reaction forces from 1.61 ± 0.64 to 1.26 ± 0.41 × BW ($P < 0.001$, ES = NA)
Ericksen [68]	32 trained, 16 control College students	Rebound jump-land	Decreased peak vertical ground reaction forces mean − 0.5 ± 0.2 N/kg ($P < 0.001$, ES = NA)
Myer [42]	18 trained High school athletes	Single-leg hop	Balance trained group decreased impact forces 7.0%, plyometric trained group increased forces 7.6% (difference between groups $P < 0.05$, ES = NA)
Sportsmetrics [15]	10 trained, 10 control College intramural basketball	Vertical jump	No improvement
Sportsmetrics [17]	11 trained, 8 control College basketball	Forward lunge, unilateral step-down	No improvement
Lephart [48]	27 trained High school athletes	Vertical jump	No improvement
Kerlan-Jobe [49]	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	No improvement
Herman [51]	33 trained, 33 control 18–30 years Recreational athletes	3 stop-jump tasks	No improvement
Wilderman [61]	15 trained, 15 control College intramural basketball	Side-step pivot	No improvement

BW body weight, *ES* effect size, *KLIP* Knee Ligament Injury Prevention Program, *MS* milliseconds, *NA* not assessed

[a] Female subjects unless otherwise indicated

6. The program must be well received by coaches and players to be successful.
7. Evaluation of success or failure of a prevention program requires large numbers of athletes and injuries.

The American Academy of Pediatrics issued the following three-part policy statement in 2014 regarding ACL injury prevention training [96]:

- Neuromuscular training appears to reduce the risk of injury in adolescent female athletes by 72%. Prevention training that incorporates plyometric and strengthening exercises, combined with feedback to athletes on proper technique, appears to be most effective.
- Pediatricians and orthopedic surgeons should direct patients at highest risk of ACL injuries (e.g., adolescent female athletes, patients with previous ACL injury, generalized ligamentous laxity, or family history of ACL injury) to appropriate resources to reduce their injury risk (http://www.aap.org/cosmf). Such discussions also should be appropriately documented in the patient's medical record.

Table 21.4 Effect of ACL intervention training on knee and hip moments

Program	Subjects[a]	Tests	Knee moments	Hip moments
Sportsmetrics [2]	11 trained, 9 control males High school athletes	Vertical jump	Decreased abduction from 3.4 to 2.1% BW × Ht ($P < 0.05$, ES = NA), adduction 4.0 to 1.9% bw × ht ($P < 0.05$, ES = NA) No improvement extension, flexion moments	No improvement abduction, adduction or flexion, extension moments
Myer [45]	41 trained, 12 control High school athletes	Drop-jump	Decreased varus from 34.0 ± 2.8 to 21.1 ± 1.7 Nm, valgus from 60.4 ± 5.5 to 43.4 ± 3.3 Nm right knee ($P < 0.001$, ES = NA) No effect varus, valgus moments left knee	NA
Myer [43]	18 trained High school athletes	Drop-jump	12 athletes with >25.25 Nm abduction moment significantly reduced ($P = 0.03$, ES = NA) 6 athletes with <25.25 Nm abduction moment did not improve	NA
Lephart [48]	27 trained High school athletes	Vertical jump	Decreased peak flexion 0.076 ± 0.038 to 0.059 ± 0.01 Nm/bw × ht. ($P = 0.01$, ES = NA) No effect peak valgus moment	Decreased flexion 0.170 ± 0.058 to 0.153 ± 0.033 Nm/bw × ht. ($P = 0.008$, ES = NA) No effect peak adduction moment
Kerlan-Jobe [49]	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	Drop-jump: decreased maximum flexion from 0.739 ± 0.37 to 0.583 ± 0.30 Nm ($P = 0.04$, ES = NA), external rotation from −0.032 ± 0.12 to 0.027 ± 0.10 Nm ($P = 0.03$, ES = NA) No effect valgus moments Stop-jump: decreased valgus from 0.863 ± 0.37 to 0.734 ± 0.31 Nm ($P = 0.04$, ES = NA) No effect flexion, external rotation moments	Drop-jump: no improvement peak flexion, abduction, or external rotation moments Stop-jump: no improvement peak flexion, abduction, or external rotation moments
Herman [50]	29 strength and feedback trained 29 feedback trained 18–30 y Recreational athletes	Stop-jump	Decreased valgus from 0.107 ± 0.060 to 0.064 ± 0.038 Nm/bw × ht ($P < 0.0001$, ES = NA) No improvement extension moment	Decreased adduction from 0.115 ± 0.064 to 0.035 ± 0.130 Nm/bw × ht ($P < 0.0001$, ES = NA)
Pfile [63]	9 plyometric trained 9 core stability trained 6 controls High school athletes	Drop-jump	Plyometric: decreased flexion mean − 0.33 ± 0.04 (P = NA, ES = 2.04), valgus 0.09 Nm/kg-m (P = NA, ES = 1.52) Core stability: no change	Plyometric: no change Core stability: decreased flexion −0.33 ± 0.05 (P = NA, ES = 1.51), internal rotation −0.06 ± 0.01 Nm/kg m (P = NA, ES = 2.21)

Table 21.4 (continued)

Program	Subjects[a]	Tests	Knee moments	Hip moments
Weltin [65]	12 perturbation and perturbation trained 12 plyometric only trained Soccer, handball, basketball players	Lateral jump, cut, both reactive	Both groups decreased flexion ($P < 0.05$, ES = 0.20) and internal rotation moments ($P < 0.001$, ES = 0.47) lateral jump No improvement cut	NA
Stearns [70]	21 trained Recreational athletes 18–25 y	Drop-jump	Decreased adductor moments from 0.06 ± 0.1 to −0.02 ± 0.1 Nm/dg ($P < 0.001$, ES = NA)	Increased extensor moment from 0.92 ± 0.2 to 1.10 ± 0.2 ($P = 0.002$, ES = NA)
Ericksen [68]	32 trained, 16 control College students	Rebound jump-land	No improvement	No improvement
Brown [69]	30 trained 3 different programs, 13 control 13–18 years athletes	Jump-land single and double-leg	No improvement	No improvement
Herman [51]	33 trained, 33 control 18–30 y Recreational athletes	3 stop-jump tasks	No improvement extension or valgus moments	No improvement adduction or internal rotation moments
PEP, modified [19]	11 trained, 11 control High school basketball	Rebound jump	No improvement valgus moment	NA

BW body weight, *ES* effect size, *FIFA* International Football Federation, *HT* height, *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program

[a] Female subjects unless otherwise indicated

- Pediatricians and orthopedic surgeons who work with schools and sports organizations are encouraged to educate athletes, parents, coaches, and sports administrators about the benefits of neuromuscular training in reducing ACL injuries and direct them to appropriate resources (http://www.aap.org/cosmf).

The ability of neuromuscular retraining programs to reduce the incidence of noncontact ACL injuries in female athletes is most likely due to the increased awareness of injury situations and changes in neuromuscular indices that improve balance, strength, and coordination; provide for safer landing, pivoting, and cutting techniques; increase joint stabilization; and enhance muscular preactivation and reactive patterns to be discussed next.

Critical Points

- Ten studies reported ACL injury rates according to athlete exposures in females:
  - Three significantly reduced ACL noncontact injury rates: Sportsmetrics, PEP, and KIPP.

- Others failed to reduce ACL noncontact injury rates:
  Poor compliance with training
  Too few ACL injuries, limited statistical power
  Lack of randomization
  Changes intervention protocols over time

21.3 Changes in Knee and Hip Kinetics and Kinematics

A wide variety of studies have been published to date which analyzed the effectiveness of knee injury prevention programs in changing kinematic or kinetic factors in female athletes [2, 4, 9–12, 15, 17, 19, 21, 24, 42–45, 48–55, 59, 61, 62, 68–70].

21.3.1 Landing Forces

Statistically significant decreases in landing forces from a vertical jump [2], step-land [24], single-leg hop [42], rebound jump-land [68], and stop-jump [50] have been reported following neuromuscular training (Table 21.3). A mean reduction of 456 N (103 pounds, 46.72 kg) during a vertical jump was reported after Sportsmetrics training [2] in female high school volleyball players (Fig. 21.1). Another study [50] reported a mean reduction of 22% during a stop-jump task after training in recreational female athletes 18–30 years of age. One study reported decreases in impact forces on a single-leg hop in a group of patients who completed a balance training program; however, a group that completed a plyometrics training program demonstrated increases in impact forces [42]. None of these studies reported ES.

In contrast, no reduction in landing forces were reported in several other investigations. These included tests involving a unilateral step-down or forward lunge [17], a vertical jump [15, 48], a drop-jump and vertical stop-jump [49], three stop-jump tasks [51], and a side-step pivot [61]. In five of these six studies, the populations under investigation were collegiate or recreational athletes ≥18 years old. Factors believed to affect the ability of ACL intervention programs to alter landing forces include age (young versus adult), athletic experience (competitive versus recreational), type of instruction, and exercise protocol [15].

Fig. 21.1 Vertical jump test on force plate

21.3.2 Knee and Hip Moments

Statistically significant decreases in potentially deleterious moments have been noted during planned tasks such as a vertical jump or drop-jump by several investigations after ACL intervention training (Table 21.4) [2, 43, 45, 48–50, 63, 65, 70]. The Sportsmetrics training program produced significant decreases in knee abduction and adduction moments on a vertical jump [2]. A similar training program resulted in significant decreases in knee internal valgus (abduction) moments of 28% and internal varus (adduction) moments of 38% on a drop-jump test [43]. A program performed in collegiate soccer and basketball players produced mixed results in terms of reduction of potentially harmful moments [49]. Statistically significant decreases in knee external rotation moments and knee flexion moments were found on a drop-jump test. However, there were no effects on hip external rotation, abduction, or flexion moments or knee valgus moments on this test. ES were not reported in any of these studies.

One study compared the effects of a 4-week core stability program with a plyometric program in knee and hip moments on a drop-jump in a small group of high school athletes [63]. In the plyometric group, significant decreases and moderate ES were noted in knee flexion and knee valgus moments. There were no changes in hip flexion or internal rotation moments. In the core stability group, significant decreases and large ES were noted in hip flexion and hip internal rotation moments; however, no changes were reported in knee moments. Another study found that either plyometric training or plyometric training combined with perturbation techniques significantly decreased knee flexion and internal rotation moments on a reactive lateral jump, with large ES noted [65]. There were no effects of either training protocol in reducing knee moments on a reactive cutting task.

21.3.3 Knee and Hip Flexion Angles

Increases in knee flexion angles on landing from various tasks following ACL intervention training have been demonstrated in several studies, although the data vary in regard to the magnitude of change and whether the improvements occurred at foot strike or during the deepest point of the land, indicated as maximum or peak knee flexion (Table 21.5) [19, 42, 44, 45, 48–50, 55, 62, 67–70]. Slight average increases in knee flexion at foot strike of 5.2° [49] and 5.8° [44] during a drop-jump test were reported in two studies, and a mean increase of 4.9° on a single-leg drop landing was found in another study [62]. One study reported a mean increase of 6.2° in knee flexion (ES 0.83) on a two-legged landing after completion of a standard neuromuscular training program [69]. However, there was no improvement in a single-leg landing task. Several other studies failed to observe an improvement in knee flexion at either foot strike or the maximum point of the landing during a variety of tasks [2, 21, 51, 53, 56, 57, 59, 61, 63]. One study found a concerning significant decrease in knee flexion after completion of either a plyometric or a core stability program [63]. The plyometric group had a mean decrease of 18.5 ± 3.6° (ES 1.79), and the core group had a mean decrease of 16.3 ± 3.4° (ES 1.88).

Several studies [21, 44, 48–50, 56, 57, 68–70] have reported statistically significant improvements in either hip flexion, abduction, adduction, external rotation, or internal rotation (Table 21.5). However, several others [2, 51, 53, 63] failed to find improvements in hip angles after intervention training.

One study of 30 athletes reported a mean increase of 8.2° in hip flexion (ES 0.52) on a two-legged landing after completion of a standard neuromuscular training program [69]. However, there was no improvement in a single-leg landing task. This was the only study located that included ES in the analysis of hip flexion angles. Increases in initial and peak hip flexion during a vertical jump were described in one study following plyometric training [48]. However, there were no improvements for initial or peak hip abduction or adduction angles. Another investigation reported significant increases in maximum hip flexion and abduction angles on a stop-jump task [50]. Significant decreases in mean hip internal rotation and increases in mean hip abduction were noted during a drop-jump test following the PEP training program [21]. One study described significant decreases in hip flexion at foot strike and in maximal hip external rotation on a stop-jump task [49].

Table 21.5 Effect of ACL intervention training on knee and hip flexion angles

Program	Subjects[a]	Tests	Knee angles	Hip angles
Myer [45]	41 trained, 12 control High school athletes	Drop-jump	Increased total flexion-extension on landing from 71.9 ± 1.4 to 76.9 ± 1.4° (right knee) and from 71.3 ± 1.5 to 77.3 ± 1.4° (left knee) ($P < 0.001$, ES = NA)	NA
Myer [42, 44]	8 trained plyometric 10 trained balance High school athletes	Drop-jump, single-leg medial drop-land, single-leg hop	Drop-jump: Plyo group increased flexion initial contact from 29.8 ± 6.6 to 35.6 ± 7.5°, peak from 93.4 ± 54.2 to 101.6 ± 50.5° ($P < 0.05$, ES = NA) No change abduction Medial drop: Balance group increased peak flexion ($P = 0.005$, ES = NA). Both groups decreased abduction initial contact and peak ($P = 0.04$, ES = NA)	Drop-jump: both groups decreased adduction at initial contact from −4.6 to −5.7°, peak from −2.1 to −3.4° ($P = 0.015$, ES = NA) Medial drop: No change adduction
Lephart [48]	27 trained High school	Vertical jump	Improved peak flexion from 62.2 ± 9.7 to 86.0 ± 35.1° (plyometric group), from 63.0 ± 18.1 to 70.9 ± 19.7° (basic training group) ($P < 0.01$, ES = NA), time to peak ($P = 0.006$, ES = NA) No change flexion at initial contact	Improved flexion initial contact from 1.9 ± 5.3 to 9.7 ± 8.7° ($P = 0.02$, ES = NA), peak from 19.6 ± 9.3 to 27.2 ± 10.5° ($P = 02$, ES = NA) No change initial contact or peak for abduction, adduction
PEP [21]	18 trained High school soccer	Drop-jump	No change peak flexion	Reduced peak internal rotation from 7.1 to 1.9° ($P = 0.01$, ES = NA), increased abduction from −4.9 to −7.7° ($P = 0.02$, ES = NA)
PEP, modified [19]	11 trained, 11 control High school basketball	Rebound jump	Increased peak flexion from 92.66 ± 4.34 to 94.27 ± 3.44° ($P = 0.02$, ES = NA) No change peak internal tibial rotation	NA
Kerlan-Jobe [49]	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	Drop-jump: Increased flexion foot strike from 29.9 ± 9.0 to 35.1 ± 7.4° ($P = 0.003$, ES = NA), stance phase from 81.3 ± 10.5 to 86.9 ± 10.3° ($P = 0.006$, ES = NA) Stop-jump: No change flexion at foot strike or stance phase, no change internal tibial rotation	Drop-jump: No change flexion, abduction, external rotation at foot strike or peak Stop-jump: Decreased flexion foot strike from 72.2 ± 11.0 to 68.0 ± 8.9°, ($P = 0.05$, ES = NA), peak external rotation from 20.0 ± 12.5 to 13.1 ± 13.8° ($P = 0.02$, ES = NA) No change abduction or internal rotation
DiStefano [55]	83 trained females 90 trained males Soccer 10–17 y	Drop-jump	Improved flexion foot strike ($P = 0.009$, ES = NA) (data not provided)	NA

Table 21.5 (continued)

Program	Subjects[a]	Tests	Knee angles	Hip angles
Herman [50]	29 trained strength and feedback 29 trained feedback 18–30 y Recreational athletes	Stop-jump	All subjects combined increased peak flexion from 27.20 ± 7.02 to 28.96 ± 5.23° ($P = 0.05$, ES = NA)	All subjects combined increased max flexion angle from 44.77 ± 10.96 to 51.80 ± 8.91° ($P < 0.001$, ES = NA), abduction angle from 8.88 ± 5.88 to 11.31 ± 8.72° ($P = 0.03$, ES = NA)
Herman [51]	33 trained, 33 control 18–30 years Recreational athletes	3 stop-jump tasks	No change peak flexion	No change peak flexion
Nagano [62]	8 trained College basketball	Single-leg drop landing	Increased flexion initial foot contact from 19.3 ± 2.5 to 24.2 ± 2.1° ($P < 0.01$, ES = NA), peak from 34.3 ± 2.5 to 40.2 ± 1.9° ($P < 0.001$, ES = NA) No change external or internal tibial rotation	NA
Letafatkar [67]	15 trained, 14 control Collegiate athletes	Drop-jump	Increased flexion initial contact ($P = 0.001$, ES = 0.4) and peak ($P = 0.001$, ES = 0.9)	NA
Ericksen [68]	32 trained, 16 control College students	Rebound jump-land	Increased peak flexion mean 11.3 ± 10.4° ($P < 0.001$, ES = NA)	Increased peak flexion mean 10.9 ± 9.4° ($P = 0.001$, ES = NA)
Brown [69]	30 trained 3 different programs, 13 control 13–18 years athletes	Jump-land single and two legged	Standard program: increased peak flexion mean 6.2° ($P < 0.05$, ES = 0.84) bilateral landings. No improvement single-leg landings	Standard program: increased peak flexion mean 8.2° ($P = 0.01$, ES = 0.52) bilateral landings. No improvement single-leg landings
Stearns [70]	21 trained Recreational athletes 18–25 years	Drop-jump	Increased peak flexion from 94.0 ± 8.5° to 98.0 ± 10.1° ($P < 0.001$, ES = NA)	Increased from 83.4 ± 7.6° to 89.9 ± 8.8° ($P < 0.05$, ES = NA)
Sportsmetrics Plyometrics only [56]	18 trained, 18 control Recreational athletes 20 ± 1 years	Single-leg squat	Decreased knee abduction from −9.23 to −5.75° ($P = 0.01$, ES = NA)	Decreased hip adduction from 10.04 to 5.70° ($P < 0.001$, ES = NA)
Functional Stabilization Training [57]	14 trained, 14 control Recreational athletes 20 ± 1 years	Single-leg squat	Decreased knee abduction from −6.86 to 1.49° ($P < 0.001$, ES = NA)	Decreased hip adduction from 7.08 to 5.19° ($P < 0.05$, ES = NA)
Pfile [63]	9 plyometric trained 9 core stability trained 6 controls High school athletes	Drop-jump	Decreased flexion mean − 18.5 ± 3.6° plyometric group (P=NA, ES = 1.79), mean − 16.3 ± 3.4° core group (P = NA, ES = 1.88)	No change hip angles both groups

(continued)

Table 21.5 (continued)

Program	Subjects[a]	Tests	Knee angles	Hip angles
Sportsmetrics [2]	11 trained females 9 control males High school	Vertical jump	No change peak flexion	No change peak flexion
Kato [59]	10 trained, 10 control College basketball	Jump shot	No change peak flexion	NA
Oslo Sports Trauma Research Center [53]	20 trained Soccer, elite team handball Adults	Side-cut	No change peak flexion	No change peak flexion
Wilderman [61]	15 trained, 15 control College intramural basketball	Side-step pivot	No change flexion initial foot contact or peak	NA

ES effect size, *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program

[a] Female subjects unless otherwise indicated

However, no significant differences were observed in hip kinematics on a drop-jump test.

21.3.4 Lower Limb Alignment

Multiple investigations have determined the effects of ACL intervention training on lower limb alignment during various jumping tasks (Table 21.6). The assessment involved either measuring the distance between the hips, knees, and ankles from a single-plane video analysis which provides a general indicator of overall lower limb alignment (absolute knee separation distance and normalized knee separation distance values, Fig. 21.2) or measuring varus-valgus angles in multiple planes.

Statistically significant improvements in knee separation distance following Sportsmetrics training have been noted by multiple studies [4, 8, 10–12]. The largest group followed (912 trained high school athletes) improved the absolute knee separation distance from 20 ± 8 cm to 27 ± 8 cm ($P < 0.0001$, ES 0.87) and the normalized knee separation distance from 47 ± 19% to 65 ± 18% ($P < 0.0001$, ES 0.97) [8]. Another group of high school female athletes improved knee separation distance a mean of 3.25 cm after completing the PEP program [19]. However, two other investigations failed to find significant improvements in lower limb alignment after participating in the PEP program [21, 22].

Only a few investigations reported improvements in knee valgus angles following training [54, 59], while several studies [21, 48–52, 55, 62, 68–70] found no training effects.

Critical Points

- Multiple studies have assessed changes in kinematic or kinetic factors in female athletes after training:
  - Landing forces (mixed results):
    May be affected by age, athletic experience, type of instruction, and exercise protocol
  - Moments:
    Majority studies decreased knee and hip moments

Table 21.6 Effect of ACL intervention training on lower limb alignment

Program	Subjects[a]	Tests	Lower limb alignment
Sportsmetrics [8]	1000 trained, 1120 control High school athletes	Drop-jump	Improved normalized knee separation distance from 47 ± 19 to 65 ± 18% ($P < 0.0001$, ES = 0.97), absolute knee separation distance from 20 ± 8 to 27 ± 8 cm ($P < 0.0001$, ES = 0.87)
Sportsmetrics Volleyball [10]	34 trained High school volleyball	Drop-jump	Improved normalized knee separation distance from 56.3 ± 19.1 to 63.3 ± 12.7% ($P = 0.04$, ES = 0.43), absolute knee separation distance from 21.1 ± 8.2 to 25.9 ± 5.2 cm ($P = 0.002$, ES = 0.70)
Sportsmetrics Volleyball [4]	16 trained High school volleyball	Drop-jump	Improved normalized knee separation distance immediately after training from 50 ± 16 to 67 ± 17% ($P < 0.01$, ES = NA) and 1 year later to 74 ± 17% ($P < 0.001$, ES = NA)
Sportsmetrics Basketball [11]	57 trained High school basketball	Drop-jump	Improved normalized knee separation distance from 44.9 ± 17.2 to 74.2 ± 18.8% ($P < 0.0001$, ES = 0.63), absolute knee separation distance from 18.5 ± 7.4 to 31.8 ± 10.36 cm ($P < 0.0001$, ES = 0.59)
Sportsmetrics Soccer [12]	62 trained High school soccer	Drop-jump	Improved normalized knee separation distance from 35.9 ± 7.4 to 54.2 ± 13.7% ($P < 0.0001$, ES = 0.64), absolute knee separation distance from 14.6 ± 3.6 to 23.1 ± 6.4 cm ($P < 0.0001$, ES = 0.63)
Kato [59]	10 trained, 10 control College basketball	Jump shot	Improved peak lower extremity angle in coronal plane from 36.9 ± 19.5 to 15.1 ± 6.5° ($P < 0.05$, ES = NA), torsion angle in horizontal plane from 22.5 ± 12.8 to 17.1 ± 4.6° ($P < 0.05$, ES = NA)
Herrington [54]	15 trained Adult elite basketball	Drop-jump, jump shot	Drop-jump: Decreased knee valgus angle, 9.8° left leg ($P = 0.002$, ES = NA), 12.3° right leg ($P = 0.0001$, ES = NA) Jump shot: Decreased knee valgus angle, 4.5° left leg ($P = 0.03$, ES = NA), 4.3° right leg ($P = 0.01$, ES = NA)
PEP, modified [19]	11 trained, 11 control High school basketball	Rebound jump	Improved knee separation distance from 17.56 ± 2.92 to 20.81 ± 1.37 cm ($P = 0.004$, ES = NA)
PEP [21]	18 trained High school soccer	Drop-jump	No change peak knee valgus angle
PEP [22]	20 trained Adult elite soccer	Drop-jump	No change knee separation distance
Lephart [48]	27 trained High school athletes	Vertical jump	No change knee valgus angle at foot strike or peak
Kerlan-Jobe [49]	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	No change knee valgus angle at foot strike or peak
Herman [51]	33 trained, 33 control Recreational athletes 18–30 years	3 stop-jump tasks	No change peak knee valgus angle
Herman [50]	29 strength and feedback trained 29 feedback trained Recreational athletes 18–30 years	Stop-jump	No change peak knee valgus angle

(continued)

Table 21.6 (continued)

Program	Subjects[a]	Tests	Lower limb alignment
DiStefano [55]	83 trained females, 90 trained males Soccer 10–17 years	Drop-jump	No change knee valgus
Nagano [62]	8 trained College basketball	Single-leg drop landing	No change valgus angle at foot strike or peak
Oslo Sports Trauma Research Center [52]	20 trained, 20 control 15–16 years Soccer, handball	Side-cut	No change valgus angle at initial contact
Ericksen [68]	32 trained, 16 control College students	Rebound jump-land	No change knee abduction angle
Brown [69]	30 trained 3 different programs, 13 control 13–18 years athletes	Jump-land single and double legged	No change peak knee abduction angle
Stearns [70]	21 trained Recreational athletes 18–25 years	Drop-jump	No change peak knee abduction angle

ES effect size, *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program; *WIPP* Warm-up for Injury Prevention and Performance

[a] Female subjects unless otherwise indicated

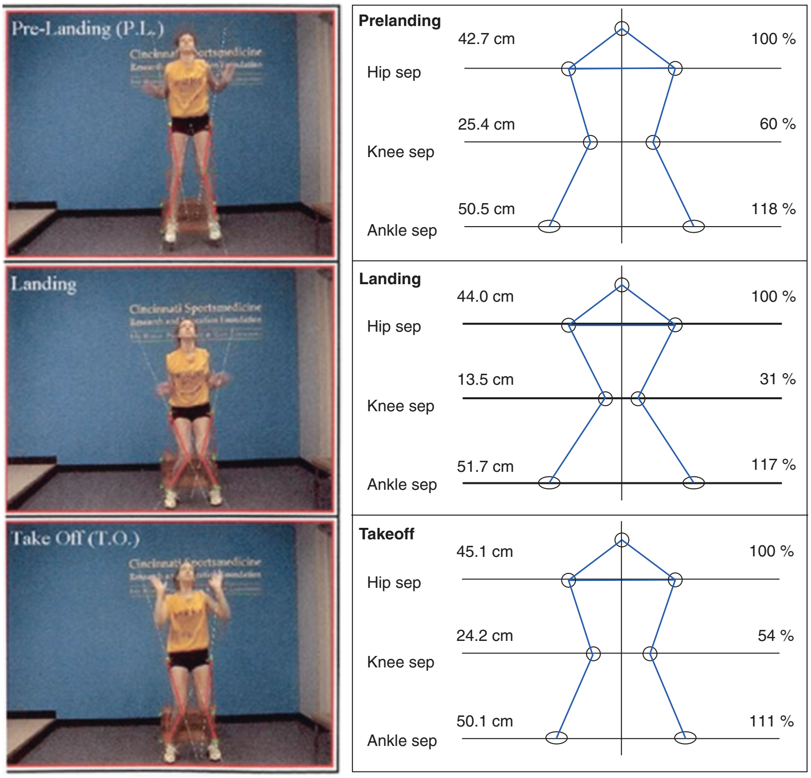

Fig. 21.2 Drop-jump video test. Three photographs are produced from the prelanding, landing, and take-off phases. The centimeters of distance between the hips, knees, and ankles are calculated along with normalized knee and ankle separation distances (according to the hip separation distance) using commercially available software (Cincinnati SportsMedicine Research and Education Foundation, Cincinnati, OH). Shown is the test result of a 16-year-old female subject before beginning the Sportsmetrics neuromuscular training program depicting poor knee separation distance and an obvious overall lower limb valgus alignment

- Knee flexion angles:
  Increased in several studies but varied in amount of change and when improvements occurred during tasks
- Hip flexion angles:
  Mixed results
- Lower limb alignment:
  Improved overall lower limb alignment in coronal plane in several studies on drop-jump test after Sportsmetrics training, but no change in knee valgus angles in multiple studies upon completion of other programs
- Several methodological problems found:
  Nearly all investigations analyzed preplanned tasks in a controlled laboratory setting.
  Few provided effect sizes or conducted prospective power analyses to determine adequate sample size.
- The determination of the magnitude of change required to actually reduce the risk of an ACL injury in knee and hip kinetic and kinematic factors remains unknown and is speculative at best.

21.4 Alterations in Lower Extremity Strength and Muscle Activation Patterns

A frequent finding among the studies included in this chapter was a statistically significant increase in lower extremity isokinetic (Fig. 21.3) or isometric strength (Table 21.7). Improvements in the strength of the hamstrings [2, 8, 9, 14, 17, 19, 22, 42, 50, 51, 57, 61, 62], quadriceps [8, 22, 48, 50, 51, 57, 99], gluteus maximum and medius [50, 51], hip abductors [19, 56, 70], and hip extensors [70] and in the hamstrings to quadriceps ratio [2, 8, 9, 14, 17, 19, 42] have been reported after 6–9 weeks of training. Only a few studies reported no improvements in muscle strength after training [13, 29, 77].

In addition, several studies [5, 16, 48, 52, 53, 58, 61, 62, 67] reported changes in electromyographic muscle activation patterns after ACL intervention training that appear to demonstrate an earlier onset of hamstrings activity, along with a reduction in quadriceps activity during drop-

Fig. 21.3 Isokinetic knee flexion-extension strength test on Biodex isokinetic dynamometer (Biodex Corporation, Shirley, NY)

Table 21.7 Effect of ACL intervention training on lower extremity strength, muscle activation patterns

Program	Subjects[a]	Tests	Isokinetic strength	Isometric strength	EMG analyses
Sportsmetrics [8]	1000 trained, 1120 control High school athletes	Isokinetic quadriceps, hamstring peak torque 300°/s	Increased hamstrings and quadriceps peak torque both legs ($P < 0.0001$, ES 0.27–0.61) and H:Q ratio both legs ($P < 0.01$, ES 0.27–0.34)	NA	NA
Sportsmetrics [16]	16 trained High school athletes	EMG during side-cut	NA	NA	10 ms post-land increased activation biceps femoris ($P < 0.01$, ES = 0.55), decreased medial hamstring to lateral hamstring co-contraction ratio
Sportsmetrics [13]	11 trained College basketball	Max voluntary isometric contraction H:Q ratio	NA	No improvement	NA
Sportsmetrics [17]	11 trained, 8 control College basketball	Isokinetic quadriceps, hamstring strength 60°/s, 300°/s	Improved hamstrings peak torque ($P = 0.008$, ES = NA) and H:Q ratio ($P = 0.04$, ES = NA) 60°/s. No effect hamstrings peak torque or H:Q ratio 300°/s. No effect quadriceps peak torque	NA	NA
Sportsmetrics [14]	11 trained, 14 control College students	Isokinetic quadriceps, hamstrings 60°/s, 120°/s	At 120°/s, improved hamstrings power from 30.76 ± 7.69 to 35.56 ± 7.92 ($P = 0.02$, ES = NA), peak torque from 24.71 ± 4.85 to 27.20 ± 5.16 ($P = 0.03$, ES = NA), H:Q ratio from 53.21 to 56.72 (P not given) No effect hamstrings power or peak torque 60°/s, quadriceps power or peak torque 60°/s or 120°/s	NA	NA
Sportsmetrics [5]	9 trained, 9 control Collegiate athletes	Drop-jump EMG analysis: preparatory, reactive phases	NA	NA	Increased hip adductor activity ($P < 0.05$, ES = NA), adductor-to-abductor muscle coactivation ($P = 0.04$, ES = NA) during preparatory phase. Improved H:Q coactivation ($P = 0.05$, ES = NA) reactive phase

Program	Subjects[a]	Tests	Isokinetic strength	Isometric strength	EMG analyses
Sportsmetrics Plyometrics only [56]	18 trained, 18 control recreational athletes 20 ± 1 years	Isokinetic eccentric quadriceps, hamstrings 60°/s; hip abductor, adductor, medial and lateral rotators 30°/s	Improved hip abductor, adductor, medial rotator peak torques. No effect quadriceps or hamstrings	NA	NA
Lephart [48]	27 trained High school athletes	Isokinetic quadriceps, hamstring peak torque 60°/s and 180°/s, isometric hip abduction peak torque, vertical jump	Improved quadriceps peak torque 60°/s and 180°/s ($P < 0.01$, ES = NA). No effect hamstrings peak torque	No improvement hip abduction peak torque	Earlier onset gluteus medius in plyometric group vs. strength group ($P < 0.05$, ES = NA), both groups greater gluteus medius preactivity ($P < 0.05$, ES = NA) Plyometric group reduced time to peak medial hamstring reactivity after foot strike ($P < 0.05$, ES = NA) No change vastus lateralis, lateral hamstring peak EMG preactivity or reactivity phases
Herman [51]	33 trained, 33 control 18–30 years Recreational athletes	Max voluntary isometric contraction	NA	Improved quadriceps, hamstrings, gluteus maximus, gluteus medius ($P < 0.001$, ES = NA)	NA

(continued)

Table 21.7 (continued)

Program	Subjects[a]	Tests	Isokinetic strength	Isometric strength	EMG analyses
Herman [50]	29 trained strength and feedback (ST-FB) 29 trained feedback 18–30 years Recreational athletes	Max voluntary isometric contraction	NA	Strength gains in ST-FB group for quadriceps, hamstrings, gluteus maximus, gluteus medius ($P < 0.001$, ES = NA)	NA
PEP [22]	20 trained Elite soccer 18.6 ± 2.7 years	Max voluntary isometric contraction quadriceps, hamstrings, gastrocnemius	NA	Improved quadriceps, hamstrings ($P < 0.001$, ES = NA)	NA
PEP, modified [19]	11 trained, 11 control High school basketball	Isokinetic quadriceps, hamstring, hip abduction, hip extension peak torque, power 60°/s	Improved peak torque, average power for all muscles tested ($P = 0.004$ to 0.04, ES = NA) and H:Q ratio. Decreased quadriceps torque ($P = 0.04$, ES = NA)	NA	NA
Wilderman [61]	15 trained, 15 control College intramural basketball	Max voluntary isometric contraction, side-step pivot	NA	NA	Increased medial hamstrings activation during loading phase ($P < 0.01$, ES = NA), decreased vastus medialis oblique activation. No effect lateral hamstrings activation
Stearns [70]	21 trained Recreational athletes 18–25 years	Max voluntary isometric contraction	NA	Increased hip extensors and hip abductors ($P = 0.01$, ES = NA)	NA

Program	Subjects[a]	Tests	Isokinetic strength	Isometric strength	EMG analyses
Hurd [58]	10 trained, 10 control males College athletes	Gait analysis, normal speed walk on perturbation platform	NA	NA	Before training, females' peak hamstring activity occurred after heel strike. After training, females had earlier onset time to peak hamstring activity (before heel strike), higher hamstrings activity, and reduced vastus lateralis activity
Oslo Sports Trauma Research Center [53]	20 trained Soccer, elite team handball, adults	Side-cut, EMG analysis	NA	NA	Greater semitendinosus muscle activity preland ($P < 0.01$, ES = NA) and land ($P < 0.05$, ES = NA) phases. Reduced activity gluteus medius preland ($P < 0.05$, ES = NA) and land ($P < 0.05$, ES = NA) phases. Reduced activity biceps femoris landing phase ($P < 0.01$, ES = NA). Reduced time to onset semitendinosus activity during preland phase ($P < 0.05$, ES = NA)
Oslo Sports Trauma Research Center [52]	20 trained, 20 control Collegiate soccer, handball	Side-cut, EMB analysis	NA	Increased hamstrings ($P = 0.01$, ES = NA)	Increased hamstrings preactivity ($P < 0.05$, ES = NA)
Nagano [62]	8 trained Collegiate basketball	Single-leg drop landing, max voluntary isometric contraction	NA	NA	Increased hamstring activity before foot strike ($P < 0.05$, ES = NA). No effect hamstring activity after foot strike. No differences rectus femoris activity, ham to quad ratio before or after foot strike
Myklebust [29]	27 trained Elite team handball, adult	Isokinetic quadriceps, hamstrings 60°/s, 240°/s	No improvement quadriceps, hamstrings, or H:Q ratio	NA	NA
Myer [42]	8 trained plyometric 10 trained balance High school athletes	Isokinetic quadriceps, hamstrings 300°/s	Improved hamstrings peak torque, H:Q ratio ($P < 0.01$, ES = NA)	NA	NA

(continued)

Table 21.7 (continued)

Program	Subjects[a]	Tests	Isokinetic strength	Isometric strength	EMG analyses
FIFA “11” [77]	17 trained, 14 control Soccer 16–18 years	Isokinetic quadriceps, hamstring peak torque 60°/s and 240°/s, isometric hip test	No improvement	No improvement hip abductors, adductors	NA
Functional Stabilization Training [57]	14 trained, 14 control Recreational athletes 20 ± 1 years	Isokinetic eccentric quadriceps, hamstrings 60°/s, hip abductor, adductor, medial, and lateral rotators 30°/s	Improved hip abductor, hip lateral rotator, hip medial rotator, knee flexor, knee extensor peak torques ($P < 0.001$, ES = NA)	NA	NA
Letafatkar [67]	15 trained, 14 control Collegiate athletes	Drop-jump, EMG analysis	NA	NA	Increased co-contraction quad to ham due to increased hamstring activity 0–50 ms and 50–150 ms after initial contact ($P = 0.001$, ES = 0.60–1.32)

ES effect size, FIFA, International Football Federation; *H:Q* hamstrings to quadriceps, *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program

[a] Female subjects unless otherwise indicated

jump, vertical jump, and side-cut activities. These alterations in muscle activation patterns are believed to be important in the prevention of ACL ruptures.

Critical Points

- Improved lower extremity muscle strength:
  - Hamstrings: ten studies
  - Quadriceps: five studies
  - Hamstrings to quadriceps ratio: six studies
- Improved hip muscle strength: two studies
- Muscle activation patterns:
  - Alterations in eight studies: earlier onset hamstrings activity, reduced quadriceps activity

21.5 Effect on Balance

Several studies have demonstrated improved balance following ACL intervention training programs (Table 21.8). The Star Excursion Balance Test has been used the most frequently to determine dynamic balance, with improvements found in reach distances in several studies [13, 40, 60, 64, 66].

Table 21.8 Effect of ACL intervention training on balance

Program	Subjects[a]	Tests	Results
Sportsmetrics [13]	11 trained College basketball	LESS, SEBT	Improved SEBT composite score ($P = 0.01$, ES = NA), LESS score ($P = 0.009$, ES = NA) immediately after training and 9 months later
Hopper [66]	13 trained, 10 control Netball, 12.17 ± 0.94 years	SEBT	Improved anterior, posteromedial, posterolateral directions ($P < 0.05$, ES = NA)
Steib [64]	21 trained, 20 control Handball, 24.0 ± 5.9 years	SEBT, single-leg stand for sway velocity	Improved all reach distances, significant differences compared with control group began at wk 6, largest differences at wk 11
Walden [38]	23 trained, 18 control 12–16 years soccer players	SEBT	No improvement
Filipa [40]	13 trained, 7 control High school soccer	SEBT	Improved SEBT composite ($P < 0.05$, ES = 0.13)
McLeod [60]	27 trained, 23 control High school athletes	BESS and SEBT	BESS: trained group fewer errors than pre-train and control group ($P = 0.03$, ES = NA) SEBT: improved anteromedial, medial, posterior, and lateral directions ($P < 0.001$, ES = NA)
Myer [47]	41 trained High school athletes	Biodex stability system: total stability index, anteroposterior stability index, medial-lateral stability index, single leg	Improved total stability ($P = 0.004$, ES = NA) and anteroposterior stability ($P = 0.001$, ES-NA)
Myklebust [29]	27 trained Elite team handball, adult	KAT 2000 balance index score single and two legs	Improved score for two legs ($P = 0.003$, ES = NA), no change single leg

BESS Balance Error Scoring System, *ES* effect size, *LESS* Landing Error Scoring System, *NA* not assessed, *SEBT* Star Excursion Balance Test

[a] Female subjects unless otherwise indicated

One study [47] involving high school athletes reported improvements in single-leg total stability and anteroposterior stability on the Biodex Stability System (Biodex Corporation, Shirley, NY, Fig. 21.4) after training. There was no improvement in medial-lateral stability in these subjects. Another investigation [60] found significant improvements in the Balance Error Scoring System, which is comprised of six different 20-s balance tests in different stances and on different surfaces. A group of 27 athletes who completed the training program had fewer errors than that recorded before training and also compared with a control group. These subjects also improved scores on the Star Excursion Balance Test in distances successfully reached with a single leg in anteromedial, medial, posterior, and lateral directions.

Fig. 21.4 Single-leg balance test on Biodex Stability System (Biodex Corporation, Shirley, NY)

Critical Point

- Improvements in Star Excursion Balance test reach distances found in several studies.

21.6 Enhancing Athletic Performance

There have been multiple studies which documented changes in athletic performance indicators following ACL injury prevention training in female athletes (Table 21.9) [5, 8, 10–12, 45, 49, 53, 54, 56, 57, 66]. Vertical jump height is one of the most common indices tested, with mixed results reported. Improvements have been noted in several studies, with mean published post-train increases ranging from 1.2 to 4 cm; however, most of the studies reported small ES [8, 10, 11, 45, 49, 53, 66]. Several other studies [12, 15, 19, 22–24, 32, 38, 77] found no significant increases in jump height after training.

Statistically significant increases in the distance hopped during various single-leg hop tests have been reported after training [8, 45, 49, 54, 56, 57]. In a study of 280 high school athletes, a mean increase in the triple crossover hop test of 33 ± 54 cm ($P < 0.0001$, ES 0.47) was found following Sportsmetrics training [8]. In a group of 18 recreational adult athletes, improvements in the triple hop test (mean, 43 cm, $P < 0.001$, ES not provided) were reported after 8 weeks of plyometric training [56]. Elite adult basketball players improved the distance on the triple hop test by a mean of 110–111 cm ($P = 0.001$, ES not provided) after 4 weeks of plyometric training [54].

Sprint times have been assessed in several investigations before and after training, with conflicting results reported. In a group of 221 high school athletes, the agility *T*-test time improved from 12.10 ± 1.01 s to 11.51 ± 0.83 s ($P < 0.0001$, ES 0.64) after Sportsmetrics training [8]. Similar findings were reported in 62 high school soccer players [12]. One study reported improvements in 10-m and 20-m sprints ($P < 0.05$, ES 1.2). However, several studies reported no improvements in sprint speed after training [5, 11, 23, 32, 38, 77].

Table 21.9 Effect of ACL intervention training on athletic performance

Program	Subjects[a]	Tests	Vertical jump	Single-leg hop tests	Speed, agility	VO_2max, core strength
Sportsmetrics [8]	1000 trained, 1120 control High school athletes	Vertical jump, single-leg triple hop and triple crossover hop, *t*-test, sprints, MSFT	Increased mean 1.3 cm ($P < 0.0001$, ES = small [value NA])	Increased triple crossover hop from 360 ± 71 to 393 ± 69 cm ($P < 0.0001$, ES = 0.47) right leg. Increased triple hop from 405 ± 96 to 414 ± 95 cm ($P = 0.003$, ES = 0.09) right leg	Improved t-test from 12.10 ± 1.01 to 11.51 ± 0.83 s ($P < 0.0001$, ES = 0.64)	Improved estimated VO_2max from 36.4 ± 5.0 to 39.2 ± 4.4 ($P < 0.0001$, ES = 0.57)
Sportsmetrics Volleyball [10]	34 trained Volleyball High school	Vertical jump, MSFT, sit-up test	Increased mean 1.2 cm from 40.1 ± 7.1 to 41.5 ± 4.5 cm ($P = 0.03$, ES = 0.24)	NA	NA	Improved estimated VO_2max from 39.4 ± 4.8 to 41.4 ± 4.0 ml/kg/min ($P < 0.001$, ES = 0.45) Increased sit-up from 37.7 ± 5.3 to 40.5 ± 5.9 reps ($P = 0.03$, ES = 0.50)
Sportsmetrics Basketball [11]	57 trained Basketball High school	Vertical jump, MSFT, 18.29-m sprint	Increased mean 2.3 cm, from 26.2 ± 12.3 to 28.5 ± 12 cm ($P < 0.0001$, ES = 0.09)	NA	No change	Improved estimated VO_2max from 34.6 ± 4.5 to 39.5 ± 5.7 ml/kg/min ($P < 0.0001$, ES = 0.43)
Sportsmetrics Soccer [12]	62 trained Soccer High school	Vertical jump, *t*-test, 37-m sprint, MSFT	Increased mean 1.3 cm, from 40.7 ± 8.9 to 42.1 ± 8.3 cm ($P = 0.04$, ES = 0.08)	NA	Improved t-test from 12.05 ± 0.87 to 11.31 ± 0.69 s ($P < 0.0001$, ES = 0.43) Improved 37-m sprint from 6.11 ± 0.43 s to 5.99 ± 0.38 s ($P = 0.02$, ES = 0.08)	Improved estimated VO_2max from 37.9 ± 4.5 to 40.1 ± 4.7 ml/kg/min ($P < 0.0001$, ES = 0.23)
Sportsmetrics Plyometrics only [56]	18 trained, 18 control recreational athletes 20 ± 1 years	Triple hop, 6-m timed hop	NA	Increased triple hop from 342 ± 51 to 385 ± 48 cm ($P < 0.001$, ES = NA), improved timed hop from 2.38 ± 0.33 s to 1.98 ± 0.28 s ($P < 0.001$, ES = NA)	NA	NA

(continued)

Table 21.9 (continued)

Program	Subjects[a]	Tests	Vertical jump	Single-leg hop tests	Speed, agility	VO_2max, core strength
Myer [45]	41 trained, 12 control High school athletes	Vertical jump, sprint 9.1-m, single-leg hop	Increased mean 3.3 cm, from 39.9 ± 0.9 to 43.2 ± 1.1 cm ($P < 0.001$, ES = NA)	Increased from 165.1 ± 3.0 to 175.5 ± 2.6 cm right leg, from 165.1 ± 2.7 to 173.6 ± 2.5 cm, left leg ($P < 0.001$, ES = NA)	Improved from 1.80 ± 0.02 to 1.73 ± 0.01 s ($P < 0.001$, ES = NA)	NA
Kerlan-Jobe [49]	30 trained College soccer, basketball	Vertical jump, timed single-leg hop	Increased mean 3.7 cm, from 45.1 ± 14.1 to 48.8 ± 13.9 cm ($P < 0.001$, ES = NA)	Improved from 2.17 ± 0.4 to 2.03 ± 0.3 s right leg, from 2.17 ± 0.4 to 2.0 ± 0.2 s left leg ($P < 0.001$, ES = NA)	NA	NA
Hopper [66]	13 trained, 10 control netball, 12.17 ± 0.94 years	Vertical jump, sprints, netball agility, netball movement	Increased mean 4 cm ($P < 0.05$, ES = 0.84)	NA	Improved 10-m, 20-m tests ($P < 0.05$, ES > 1.2), improved netball agility ($P < 0.05$, ES = 0.98) and movement ($P < 0.001$, ES = 2.7)	NA
Chimera [5]	9 trained, 9 control Collegiate athletes	Vertical jump, 36.57-m sprint	Improved 5.8% (mean 2.54 ± 2.97 cm, $P = 0.009$, ES = NA), but not significantly different from control group	NA	Improved, but not significantly different from control group	NA
Oslo Sports Trauma Research Center [53]	20 trained, 8 control Elite handball, soccer adult	Vertical jump	Increased from 27 ± 4 to 29 ± 4 cm ($P < 0.001$, ES = NA)	NA	NA	NA
Herrington [54]	15 trained Elite basketball 18–22 years	Single-leg triple crossover hop test	NA	Increased mean 111 cm left leg, 110 cm right leg ($P = 0.001$, ES = NA)	NA	NA
Functional Stabilization Training [57]	14 trained, 14 control Recreational athletes 20 ± 1 years	Triple hop, 6-m timed hop	NA	Increased triple hop from 352 ± 37 to 392 ± 43 cm ($P < 0.001$, ES = NA), improved timed hop from 2.43 ± 0.27 s to 2.14 ± 0.21 s ($P < 0.01$, ES = NA)	NA	NA

Program	Subjects[a]	Tests	Vertical jump	Single-leg hop tests	Speed, agility	VO_2max, core strength
PEP [23]	15 trained, 16 control Soccer Adolescents	Countermovement vertical jump, 9.1, 18.3, 27.4, 36.6-m sprints, Illinois agility, pro-agility	No change	NA	No change	NA
PEP [22]	20 trained Elite soccer 18.6 ± 2.7 years	Vertical jump	No change	NA	NA	NA
PEP, modified [19]	11 trained, 11 control High school basketball	Rebound jump	No change	NA	NA	NA
Panasen [33]	119 trained, 103 control Floorball teams	Vertical jump, figure-eight run	No change	NA	No change	NA
KLIP [24]	14 trained, 14 control College students	Vertical jump	No change	NA	NA	NA
FIFA “11” [77]	17 trained, 14 control Soccer players 16–18 y	Vertical jump, sprint running, soccer skill tests	No change	NA	No change	NA
Vescovi [15]	10 trained, 10 control College intramural basketball	Vertical jump	No change	NA	NA	NA
Walden [38]	12 trained, 18 control 12–16 years soccer players	Vertical jump, triple hop, sprints	No change	No change	No change	NA

ES effect size, *FIFA,* International Football Federation; *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program, and *KLIP* Knee Ligament Injury Prevention Program

[a] Female subjects unless otherwise indicated

Estimated VO_2max has been measured following Sportsmetrics training using the multistage fitness test [100]. One study [10] involving 34 female high school volleyball players reported a mean improvement following training from 39.4 ± 4.8 to 41.4 ± 4.0 mL/kg/min ($P < 0.001$, ES 0.45). A second study [11] of 57 female high school basketball players reported a mean improvement from 34.6 ± 4.5 to 39.5 ± 5.7 mL/kg/min ($P < 0.0001$, ES 0.43). A third investigation [12] of female high school soccer players found a mean improvement from 37.9 ± 4.5 to 410.1 ± 4.7 mL/kg/min ($P < 0.0001$, ES 0.23).

Critical Points

- Vertical jump height: mixed results
- Single-leg hop: distance hopped consistently improved
- Sprint tests: mixed results
- Agility tests: consistently improved
- Estimated VO_2max: improved after Sportsmetrics training

Conclusions

Few ACL intervention training programs have undergone rigorous investigation regarding their effectiveness in reducing injury rates, improving potentially deleterious lower limb kinematic and kinetic factors, and enhancing athletic performance indicators. Only three programs significantly reduced the incidence of noncontact ACL injuries (Sportsmetrics, PEP, and KIPP). At the time of writing, only one investigation on the effectiveness of KIPP program (on reducing landing impact forces) had been published; no other analyses of this program in terms of kinematic or kinetic factors were available. The PEP program, studied in four investigations [15, 19, 21, 22], showed little effect in improving the knee valgus moment, knee valgus angle, vertical jump height, sprint time, and agility. However, this program did result in increased knee flexion and hip abduction, decreased hip internal rotation, and improvements in the strength of the quadriceps and hamstrings. The Sportsmetrics program has been analyzed in several investigations, both within the authors' center [2–4, 6–12, 16] and at independent institutions [5, 13–15, 17]. The majority of studies have shown improvements in lower limb alignment, hamstrings strength, hamstrings to quadriceps ratio, vertical jump height, single-leg hop test distances, speed, and estimated maximal aerobic capacity. Future investigations should prospectively determine adequate sample size using power analyses, report ES in addition to P values, and analyze unplanned, reactive tests in laboratory studies.

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Part IV

Reducing the Risk of Reinjury After ACL Reconstruction

22

Rehabilitation After ACL Reconstruction

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Abstract

This chapter reviews the scientific principles and concepts for anterior cruciate ligament reconstruction postoperative rehabilitation programs. The exercises and modalities used in each phase of the programs are presented, along with signs and symptoms to recognize and treat to prevent a complication such as loss of knee motion. Criteria are provided to advance the patient through the programs in a manner that is safe to the healing graft and responsive to the patient's final activity level goals. Advanced neuromuscular retraining is advocated for patients who desire to return to high-risk activities such as soccer and basketball. Criteria for final release to unrestricted athletics are provided.

22.1 Introduction and Clinical Concepts

The majority of patients who sustain anterior cruciate ligament (ACL) injuries and undergo reconstruction are athletes under 25 years of age who are frequently involved in high school, collegiate, or league sports. The major goals of this operation for these individuals are to stabilize the knee to prevent future reinjuries and allow a safe return to previous athletic activity levels. Although these goals are successfully achieved in many patients, a review of clinical studies revealed reinjury rates ranging from 3% to 22% (see also Chap. 4) [1–19]. These rates included either a rupture to the ACL graft or an injury to the contralateral ACL. Some of the most frequently cited factors statistically 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. 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.

One problem that exists is a lack of consensus 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 over the last decade to determine when return to unrestricted athletics is appropriate [20].

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Of the 264 studies review, only 35 (13%) discussed objective criteria required for return to athletics. These criteria included 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). This systematic review demonstrated a lack of evidence of objective assessment in the literature prior to release to unrestricted sports activities.

We believe that a comprehensive rehabilitation program following ACL reconstruction is crucial to enable patients to return to high-risk sports activities as safely as possible. Because of the published documentation of neuromuscular deficits in both the reconstructed and contralateral limbs postoperatively [21], failure to address and fully rehabilitate both knees may also be a factor for high postoperative reinjury rates. This chapter provides our recommendations for exercises and goals for each phase of rehabilitation, as well as extensive criteria required for release to high-level athletics, based on over three decades of experience and multiple clinical studies [22–27].

In order for an ACL rehabilitation program to be successful in regaining normal knee function, many factors must be taken into account that may influence the eventual outcome [28]. These include obtaining a full range of knee motion; normal gait mechanics; adequate lower extremity, upper extremity, and core muscle strength required for the desired activity level; and normal bilateral proprioception and neuromuscular function using exercises and modalities that are not deleterious to the healing graft. The exercise program should not produce harmful forces on the patellofemoral or tibiofemoral compartments, result in chronic joint effusions, or cause tendinitis. There are many factors that impact these goals, some are influenced by the injury itself, others are based on the skill of the surgeon in terms of graft placement and treatment of concomitant injuries, and others are under the control of the therapy team. Patient motivation and compliance are also key factors in the eventual outcome.

The ACL and knee joint capsule contain mechanoreceptors which provide information regarding joint position to the central nervous system for communication with muscles to provide dynamic protection to the joint [29–31]. This proprioceptive behavior has been defined in terms of static awareness of joint position in space, kinesthetic awareness (detection of limb movement and acceleration), and closed-loop afferent activity required for a reflex response and the regulation of muscle stiffness [32, 33]. Control of posture and balance, either static or dynamic, is dependent on sensory information gained from proprioception and the vestibular and visual systems. Impairment of any of these factors may effect postural control.

Complete ACL ruptures may result in abnormal gait patterns, muscle strength and activation patterns, neuromuscular function, and proprioception which may last many months or even years after the injury or surgery [34–37]. ACL reconstruction followed by traditional strength training may not correct these abnormalities. Therefore, neuromuscular retraining is recognized as an essential component of ACL rehabilitation programs [14, 28, 38, 39].

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. These risks cannot be predicted, and patients are cautioned to return to strenuous activities carefully and avoid any activity in which pain, swelling, or a feeling of instability develops. The early return to athletics is not encouraged 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. 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 [28].

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 7% to 40%.
  - Multiple reasons for reinjuries, ACL graft failure
- Lack of consensus exists on criteria for release to unrestricted sports.
- 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

22.2 Protocol for Primary ACL Bone-Patellar Tendon-Bone Autogenous Reconstruction: Early Return to Strenuous Activities

22.2.1 Early Postoperative Rehabilitation: Weeks 1–6

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 at least 0°–135° of knee range of motion (ROM), resume full weight bearing with a normal gait pattern, and recover adequate strength of the lower extremity and hip musculatures (Table 22.1). This is the time period to recognize and treat early postoperative problems such as the inability to regain knee motion according to the goals to be described, development of a pain syndrome, early onset of graft stretching, or the development of patellar tendon or patellofemoral pain.

The first postoperative week is a critical time period in regard to control of knee joint pain and swelling (Table 22.2). 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. Control of knee effusion and pain is required to avoid a quadriceps inhibition phenomenon and allow the immediate exercise protocol to be performed effectively. Modalities such as high-intensity electrical muscle stimulation, biofeedback, and cryotherapy are used as required to control pain and swelling, achieve an adequate quadriceps contraction, and regain normal knee flexion and extension.

Table 22.1 Goals of each phase of rehabilitation

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 two 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 two tests): ≤15% deficit compared to uninvolved limb

ROM range of motion, *KT* knee arthrometer

Table 22.2 Cincinnati Sportsmedicine and Orthopaedic Center rehabilitation protocol for primary ACL reconstruction: early return to strenuous activities

	Postoperative week					Postoperative 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, gastroc-soleus, iliotibial band, quadriceps	X	X	X	X	X	X	X	X	X

Table 22.2 (continued)

	Postoperative week					Postoperative month			
	1–2	3–4	5–6	7–8	9–12	4	5	6	7–12
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			X	X	X	X	X	X	X
Ski machine			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, see text

The protocol for prevention of deep venous thrombosis includes one aspirin a day for 10 days and use of a bulky compression 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. Aspiration is performed for knee joint hemarthrosis. Nonsteroidal anti-inflammatories are used for at least 5 days postoperative.

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. 22.1). 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. 22.2). At least 0° of knee extension should be obtained by the second week (Table 22.3). Knee flexion is gradually increased to 135° by the fifth to sixth week.

Patients who fail to achieve these motion goals should be placed into the treatment protocols shown in Table 22.4 [40]. If required, exercises and modalities to obtain gentle overpressure are usually successful in restoring full extension and flexion. For knee extension, a hanging weight regimen may be initiated on the seventh postoperative day in which the foot and ankle are propped on a towel or other device to elevate the

Fig. 22.1 Passive range of knee motion exercises done by (**a**–**c**) the patient or (**d**) the therapist

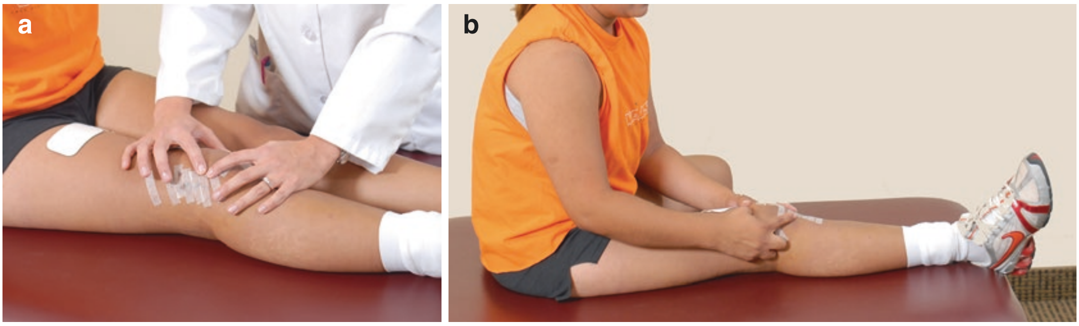


Fig. 22.2 Patella mobilization performed by (**a**) the therapist or (**b**) the patient

hamstrings and gastrocnemius (Fig. 22.3). This position is maintained for 10 min per session and repeated 4–8 times a day. 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. 22.4). Failure to obtain full knee motion

Table 22.3 Range of motion, flexibility, and modalities

Time postoperative	Range of motion (10 min)	Patellar mobilization (5 min, before knee motion exercises)	Flexibility (5 reps × 30 s)	Electrical muscle stimulation (20 min)	Biofeedback (20 min)	Cryotherapy (20 min)
1–2 weeks	3–4 times per day	Medial-lateral Superior-inferior	Hamstring, Gastroc-soleus	Yes	Yes	Yes
3–4 weeks	3–4 times per day	Medial-lateral Superior-inferior	Hamstring, Gastroc-soleus	Yes	Yes	Yes
5–6 weeks	3 times per day	Medial-lateral Superior-inferior	Hamstring, Gastroc-soleus	Yes	Yes	Yes
7 weeks–beyond		Should be normal	Hamstring, Gastroc-soleus, quadriceps, iliotibial band			Yes

Table 22.4 Protocols for limitation of knee motion

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 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 times per day
    – Add more weight (up to 25 lb) if full extension 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

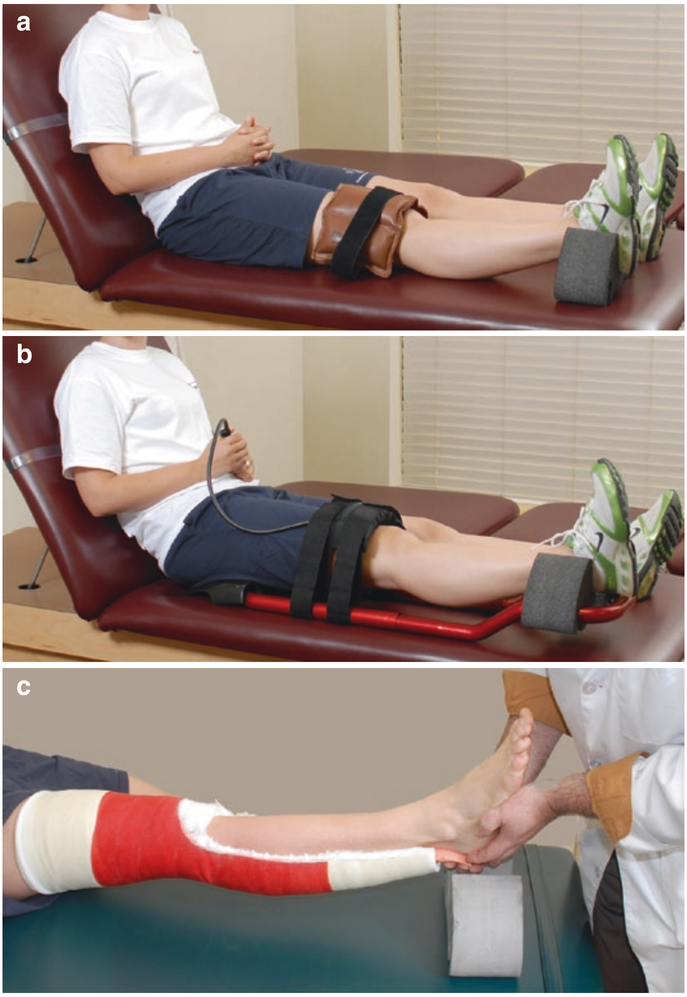
will greatly hinder the patient's ability to reach other rehabilitation goals, and therefore, any problems achieving flexion and extension should be addressed during the initial postoperative period. Patients who have difficulty achieving 90° by the fourth postoperative week require a gentle ranging of the knee under anesthesia as described elsewhere [40].

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.

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 (Table 22.5). Closed kinetic chain exercises are initiated the first postoperative week, including mini-squats and the leg press machine (Fig. 22.5). 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.

Open kinetic chain extension exercises are also begun after the first four postoperative weeks to further develop quadriceps muscle strength. Caution is warranted due to the potential problems

Fig. 22.3 Overpressure extension exercises using (**a**) a hanging weight and (**b**) an extension board. A drop-out cast (**c**) may be used for resistant cases



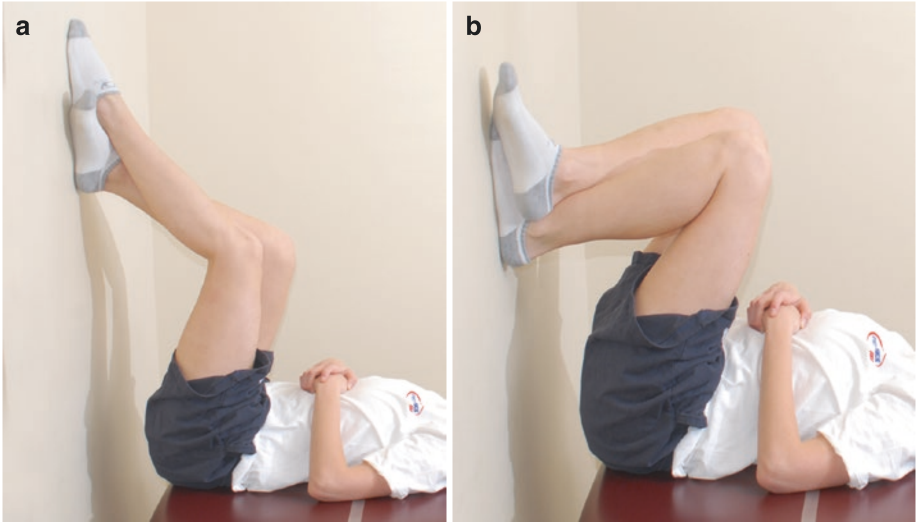


Fig. 22.4 Overpressure flexion exercises using (**a**, **b**) wall sliding technique and (**c**, **d**) commercially available knee flexion devices

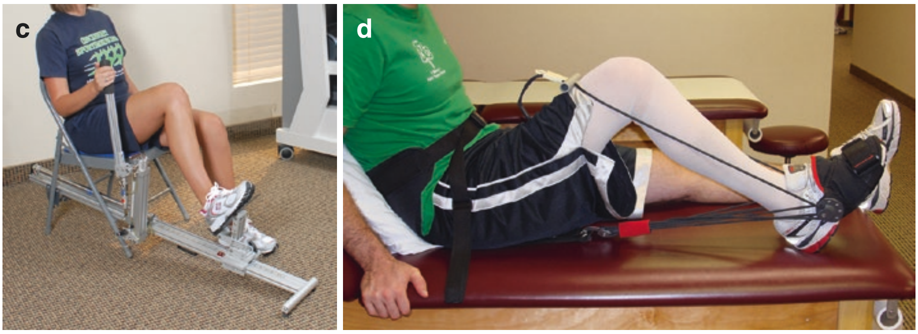


Fig. 22.4 (continued)

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 due to the forces placed on the patellofemoral joint and ACL graft. 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.

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 on a multi-hip or cable system or a hip abductor/adductor machine (Fig. 22.6), using a side-lying "clam" exercise with (or without) a resistance band (Fig. 22.7), walking with exaggerated hip flexion with (or without) a resistance band (Fig. 22.8), 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. 22.9) and processing to single-leg raises. Importantly, upper body weight training and dynamic hip and core training are initiated 5–6 weeks postoperative.

Balance and proprioceptive training are begun the first postoperative week (Table 22.6) 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. 22.10a). Half foam rolls are also used as part of the gait retraining and balance program (Fig. 22.10b). 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. 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.

Aerobic conditioning may begin the first week with an upper body cycle machine (Biodex Medical Systems, Shirley, NY) if available (Table 22.7). 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.

Table 22.5 Muscle strengthening exercises

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		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 per day 20 min		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 per day 20–30 min 3 times per week machines		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
27 weeks–beyond 3–4 times per week 20–30 min 3 times per week machines		Resistance band, High speed, 3 sets × 30 reps	With resistance: 1–2 sets × 8–12 reps				1–2 sets × 8–12 reps	1–2 sets × 8–12 reps	1–2 sets × 8–12 reps

Reps Repetitions

Fig. 22.5 Closed kinetic chain exercises begun the first postoperative week include (**a**) mini-squats, (**b**) wall sits, and (**c**) the leg press machine

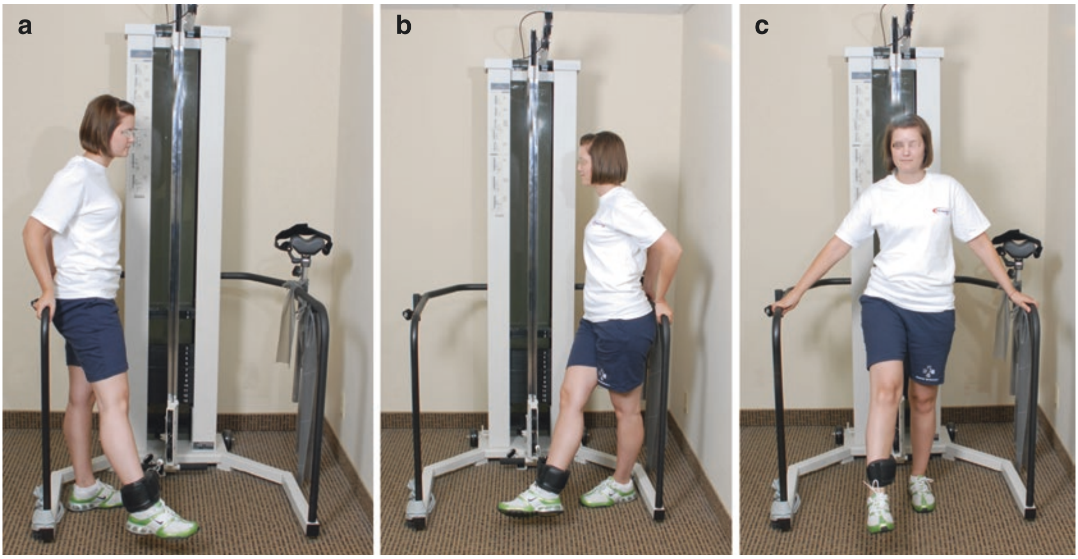


Fig. 22.6 The hip abductors (**a**), adductors (**b**), and flexor (**c**) muscle groups exercised on a cable system machine

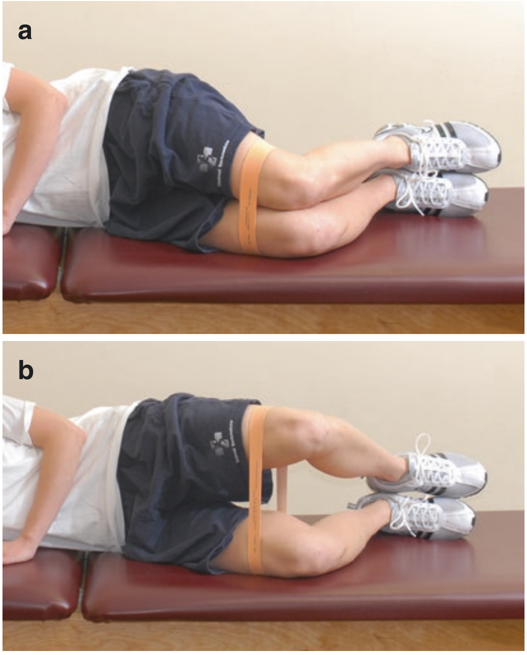


Fig. 22.7 The hip abductors exercised using a side-lying "clam" exercise which may be performed with (**a**, **b**) or without a resistance band

Fig. 22.8 Walking with exaggerated hip flexion may be done with or without a resistance band

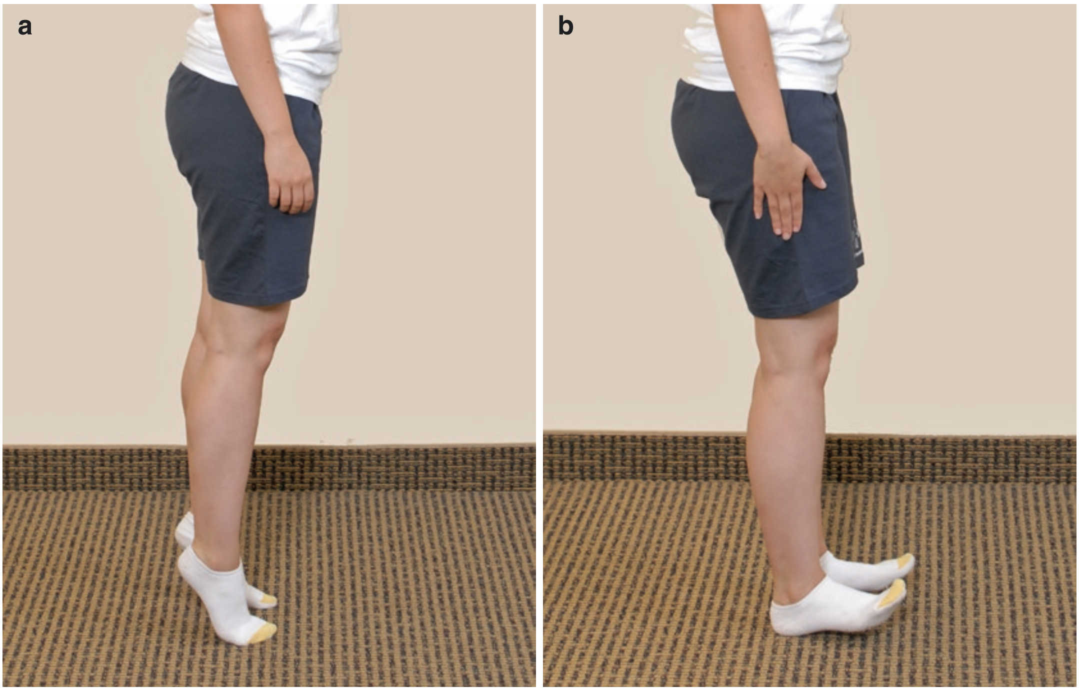


Fig. 22.9 Strength of the gastrocnemius and soleus muscles initially recovered using (**a**) toe raises and (**b**) heel raises

Critical Points

- Goals: control pain and swelling, regain 0°–135°, assume full weight bearing with normal gait, and regain strength lower extremity.
- Recognize and treat problems early postoperatively.
- First postoperative week critical: control pain and swelling, demonstrate adequate quadriceps contraction, and begin immediate knee motion and strengthening exercises.
- Modalities used as required.
- Begin extension, flexion overpressure program if 0°–90° not achieved by seventh postoperative day.
- Full lower extremity strengthening, balance, proprioceptive training, aerobic conditioning performed.

22.2.2 Intermediate Phase: Weeks 7–12

The goals of this portion of the rehabilitation program are to improve lower extremity muscle strength (to a 4/5 on manual testing); maintain no pain, swelling, or instability as the patient progresses; demonstrate a full ROM with normal patellar mobility; and begin the running program if specific criteria are achieved.

Muscle strengthening exercises are progressed as shown in Table 22.5. 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. 22.11a, 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. 22.11c). They may also perform controlled single-leg hops in specific directions by balancing first on the normal contralateral limb (Fig. 22.12a), hopping and landing on the reconstructed limb in a controlled manner (Fig. 22.12b), and then returning to the starting position, balanced on the normal limb (Fig. 22.12c).

Table 22.6 Balance and proprioception exercises

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	2-legged	Perform	Level surface 5 reps				
5–6 weeks	3 times per day 5 min		2-legged		Level surface	2–4″ block			
7–8 weeks	3 times per day 5 min		2-legged		Stable versus unstable platform	4–6″ block	Start	Start	Start
9–12 weeks	3 times per day 5 min		2-legged		Unstable platform	6–8″ block	Continue	Continue	Continue
13–26 weeks	3 times per day 5 min		Single leg		Unstable platform, add secondary activity				
27 weeks–beyond	3 times per day 5 min		Single leg		Unstable platform with secondary activity				

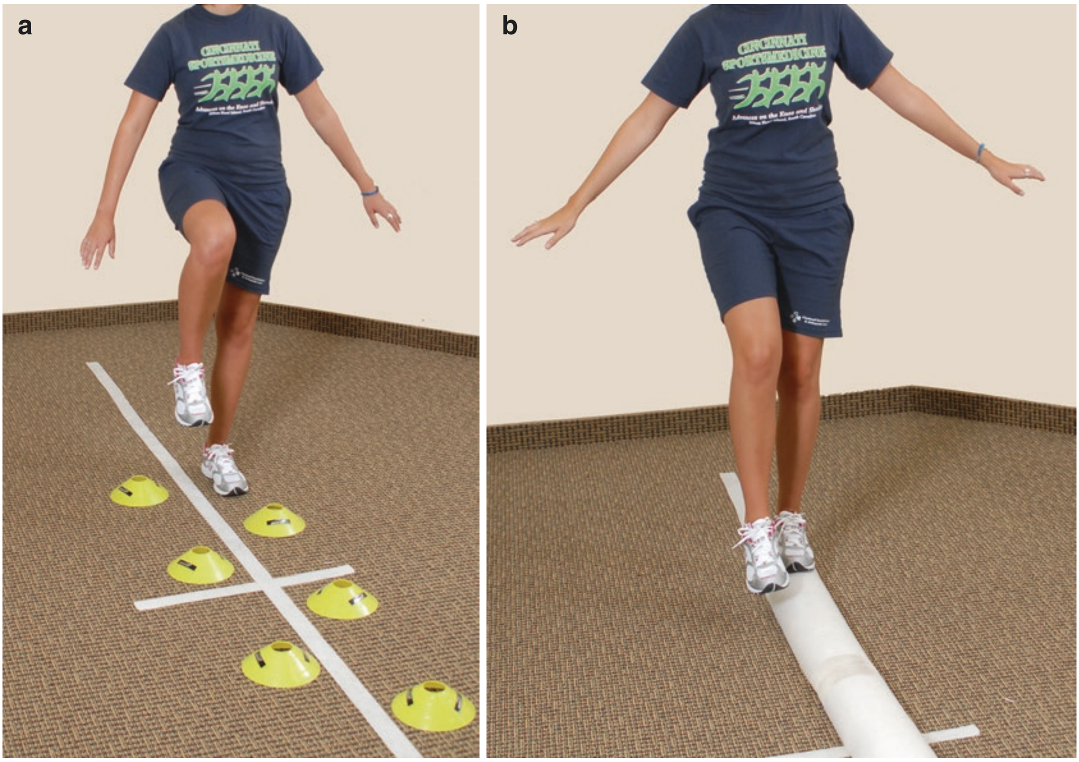


Fig. 22.10 The early gait retraining and balance program includes walking (**a**) over cups or cones and (**b**) on half foam rolls

Perturbation training techniques are begun at approximately the seventh to eighth postoperative week to further promote balance and neuromuscular control. The therapist stands behind the patient and disrupts their body posture, position, and the platform periodically to enhance dynamic knee stability (Fig. 22.13). Aerobic conditioning continues, and patients are encouraged to spend at least 3 days a week in 20–25-min sessions using either a stationary bicycle, stair machine, ski machine, elliptical machine, or swimming.

Critical Points

- Goals: improve muscle strength, no pain, swelling, giving way, full range of motion, normal patellar mobility
- Perturbation training incorporated for balance, neuromuscular control
- Aerobic conditioning 3 days a week

22.2.3 Intensive Training Phase: Weeks 13–Beyond

The goals of this phase of rehabilitation are to resume normal lower extremity strength, balance, proprioception, running speed, and agility required to return to full sports activities. Patients are allowed to begin the running program when they demonstrate no more than a 30% deficit on isokinetic testing 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 milestones as early as 9 weeks after surgery, the majority are 16–20 weeks postoperative.

Muscle strengthening exercises are continued with weight machines three times per week. Aerobic conditioning is advanced as tolerated

Table 22.7 Aerobic conditioning exercises[a]

Time postop, frequency, duration	Upper body cycle	Bicycle (stationary)	Water walking	Swimming	Walking	Stair machine (low resistance, low stroke)	Ski machine (short stride, level, low resistance)	Elliptical machine (low resistance)	Running program	Cutting	Plyometrics
1–2 weeks 1–2 times per day 5 min	OK										
3–4 weeks 2 times per day 5 min	OK	OK	OK								
5–6 weeks 2 times per day 10 min	OK	OK	OK			OK	OK				
7–8 weeks 1–2 times per day 15–20 min		OK	OK	OK	OK	OK	OK				
9–12 weeks 3 times per week 15–20 min		OK	OK	OK	OK	OK	OK	OK	Begin if conditions are met[b]		
13–26 weeks 3 times per week 20–30 min		OK	OK	OK	OK	OK	OK	OK	Begin or progress	Begin if conditions are met[b]	Begin if conditions are met[b]
27 weeks–beyond 3 times per week 20–30 min		OK	OK	OK	OK	OK	OK	OK	Begin or progress	Begin or progress	Begin Sportsmetrics program for high-risk sports if conditions are met[b]

[a] Patient selects one exercise for each session

[b] See text

Fig. 22.11 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

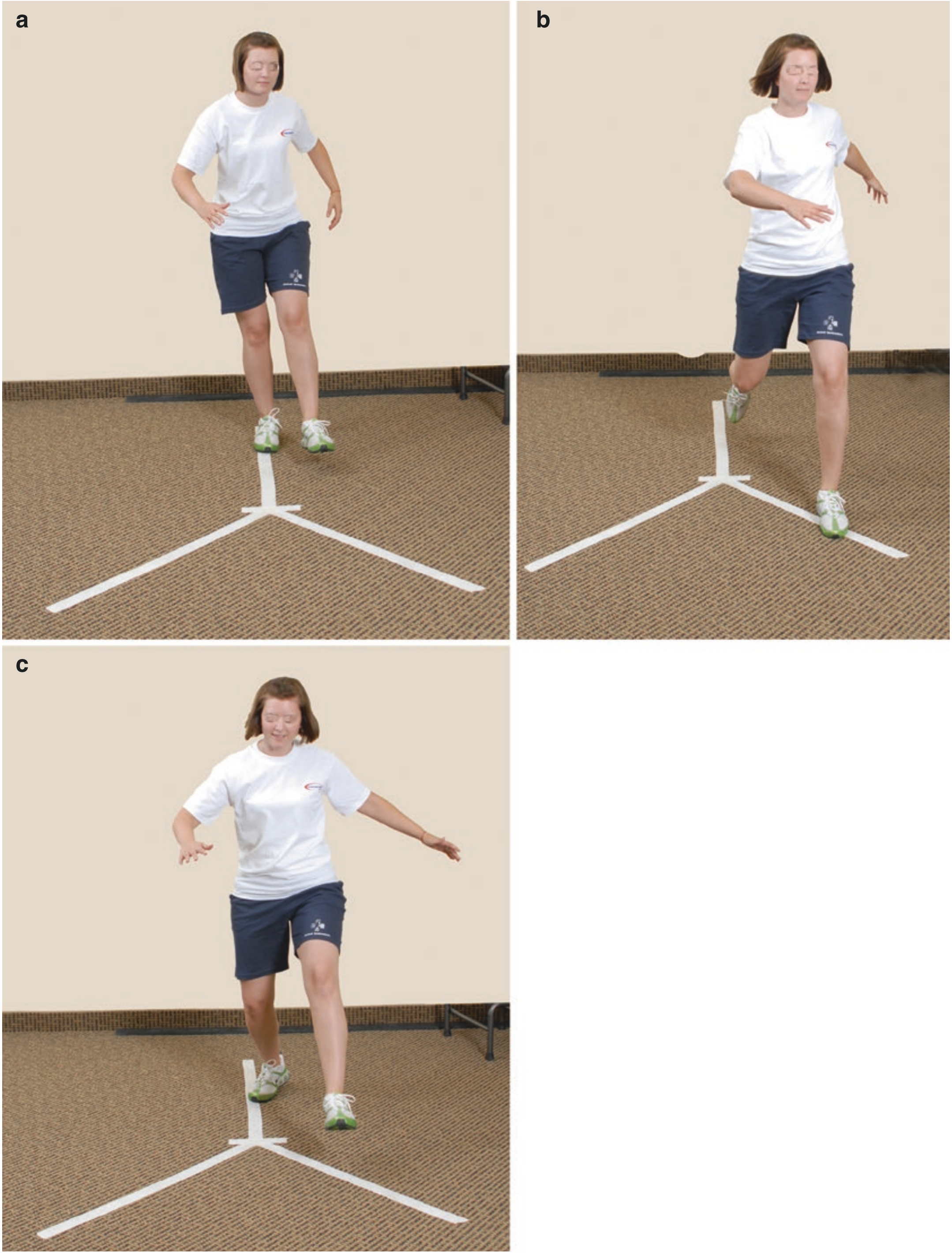


Fig. 22.12 Controlled single-leg directional hopping and balancing (**a**–**c**)

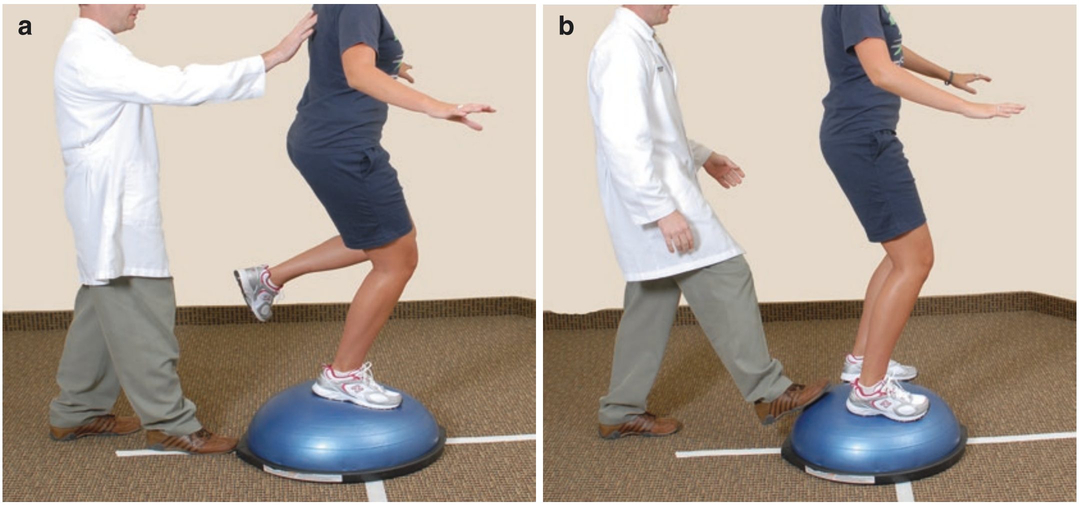


Fig. 22.13 Perturbation training performed by using direct contact with either the (**a**) patient or (**b**) platform

and continued when the running program is initiated. Upon completion of the running program, a basic plyometric exercise routine is begun as described below. Only after the patient has successfully completed these programs may they enter into the final phase of rehabilitation which involves more intense plyometric and agility drills.

Critical Points

- Goals: resume normal strength, balance, proprioception, running speed, and agility to return to sports.
- Running program begun when criteria met, then basic plyometric program.
- Final phase: advanced plyometric, agility drills before return to high-level sports.

22.2.4 Running and Agility Program

In our experience, most patients are able to begin the running program at approximately 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.

The running program is designed 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. The running program is performed three times per week, on opposite days of the strength program. Since the running program may not reach aerobic levels 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. There are four levels in the running program:

- Level I:
  - 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 2–3 times length of training
- Level II:
  - Lateral running, crossover maneuvers over 20 yards (18.29 m)

  - Side-to-side running over cups
  - Sports-specific equipment used to enhance skill development
- Level III:
  - Figure-eight drills over 20 yards (18.29 m) and then decrease to 10 yards (9.14 m)
- Level IV:
  - Cutting patterns, directional changes at 45° and 90° angles, progress from subtle to sharp cuts

Critical Points

- Usually begun 16–20 weeks postoperative.
- Criteria:
  - ≤30% deficit isokinetic peak torque quadriceps, hamstrings
  - Normal Lachman
  - No pain, swelling, instability with all other rehabilitation exercises
- Use a track to control surface, terrain, and distance.
- First level: straight walk/run combinations (20, 40, 60, and 100 yards forward, backward).
- Second level: lateral running, crossover maneuvers over short distances.
- Third level: figure-8 drills.
- Fourth level: cutting patterns, directional changes at 45°, 90° angles.

22.2.5 Basic Plyometric Training Program

Plyometric training is begun upon successful completion of the running program in order to minimize bilateral alterations in neuromuscular function and proprioception. The 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, as well as adequate stability to the foot.

During the various 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. 22.14).

Plyometric training is performed 2–3 times weekly. Individual sessions are accomplished in a manner similar to interval training. Initially, the rest period lasts two to three times the length of the exercise period which is gradually decreased to one to two times. The initial exercise time period is 15 s per direction. The patient is asked to complete as many hops between the squares as possible in 15 s. Three sets are performed for both directions and the number of hops recorded. The program is progressed as the number of hops increases, along with patient confidence. There are six levels in the basic plyometric training program:

- Level I: level surface box hopping, both legs, four-square grid on floor
  - Front-back
  - Side-side
- Level II: level surface box hopping, both legs
  - Hop in L-shaped and reverse L-shaped directions
- Level III: level surface box hopping, both legs
  - Diagonal (Fig. 22.15)
- Level IV: level surface box hopping, both legs
  - Pivot hops, 90° and 180° directions (Fig. 22.16)
- Level V: level surface box hopping, single leg
  - Front-back
  - Side-side
  - Diagonal
  - Pivot hops, 90° and 180° directions
- Level VI: vertical box hops

Critical Points

- Begun after successful completion of running program.
- Avoid very hard surfaces.

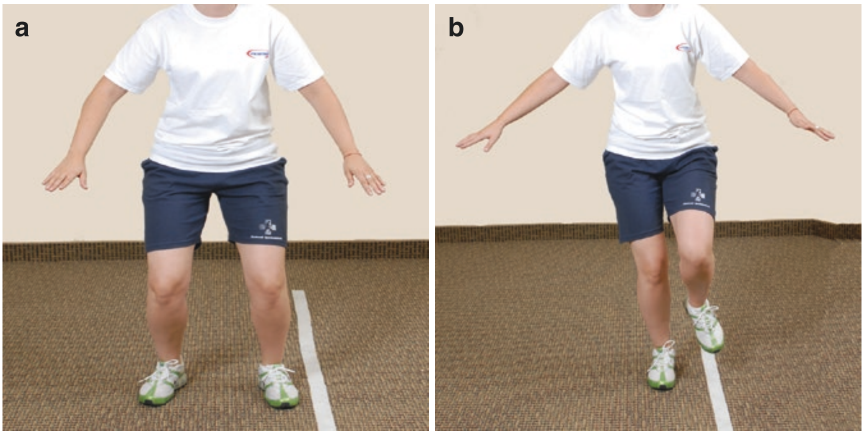


Fig. 22.14 Plyometric training with demonstration of proper landing positions for (**a**) double-leg and (**b**) single-leg jumps

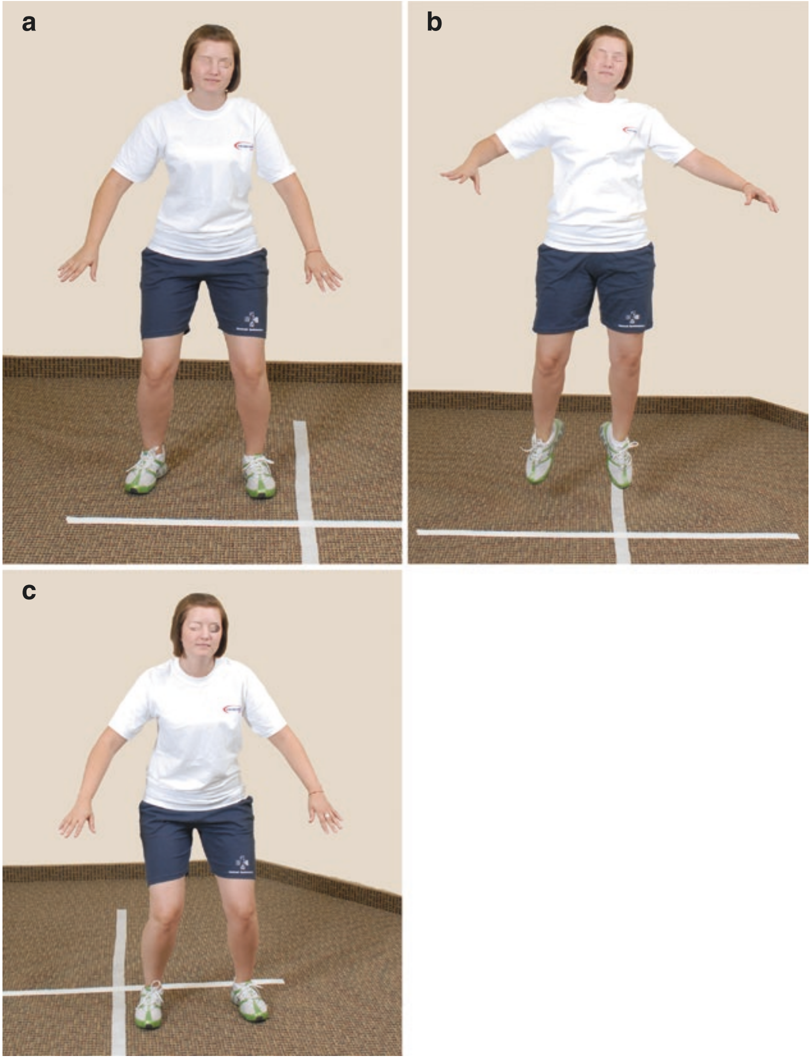


Fig. 22.15 Beginning plyometrics, Level I: level surface box hopping using both legs in a diagonal pattern (**a**–**c**)

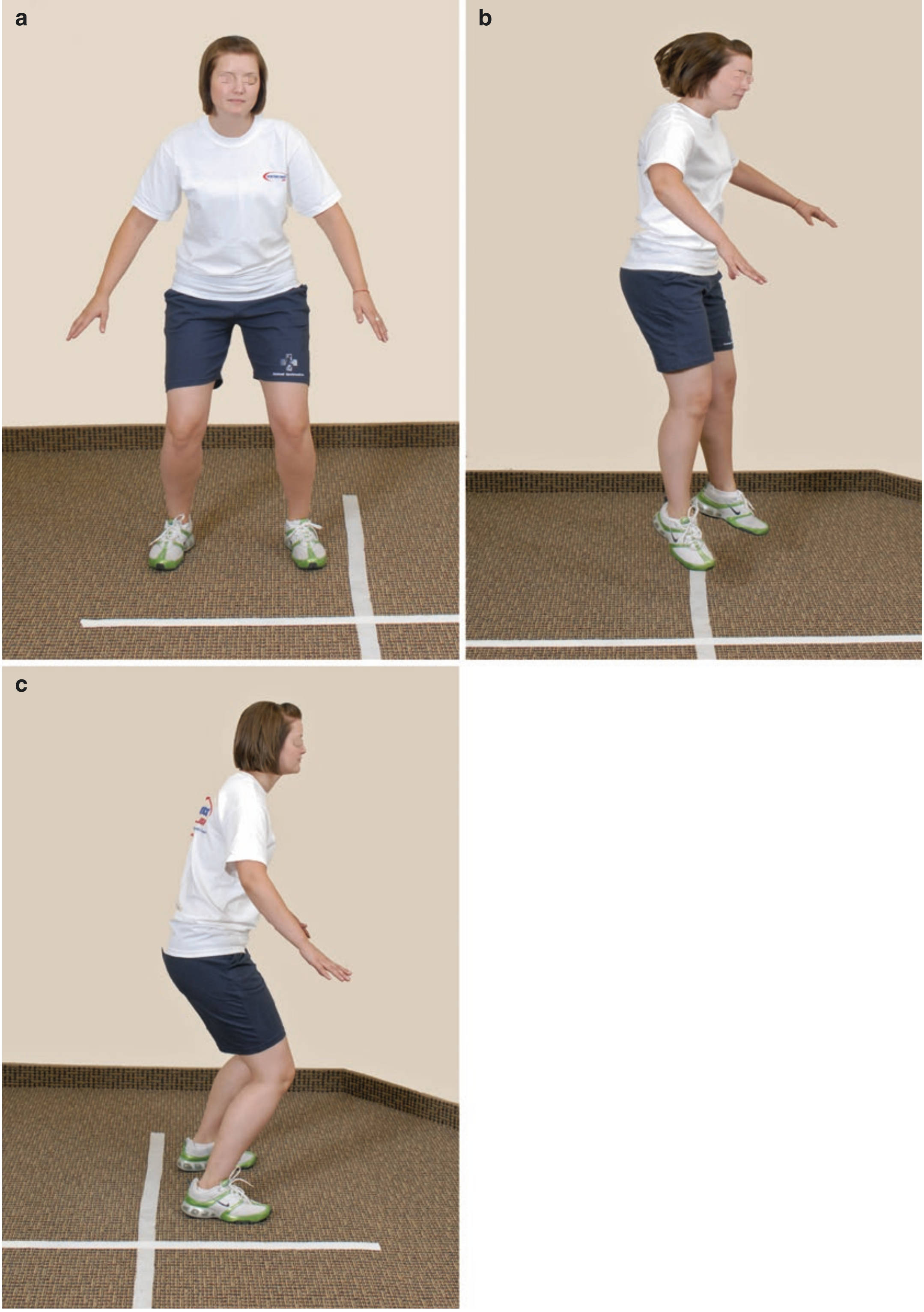


Fig. 22.16 Beginning plyometrics, Level I: level surface box hopping using both legs in a 90° pattern (**a**–**c**)

- Proper mechanics, body position emphasized.
- Level surface box hops, use both legs, four-square grid.
- Progress to single-leg hops, vertical box hops.
- Perform two to three times/week.

22.2.6 Advanced Neuromuscular Retraining

Advanced neuromuscular retraining such as the Sportsmetrics program is advocated as end-stage rehabilitation for all patients returning to high-risk sports activities that involve pivoting, cutting, and jumping/landing after ACL reconstruction. Whenever possible, each training session should be done under the supervision of a certified instructor, athletic trainer, or physical therapist. In order for a patient to begin this final phase of rehabilitation, the following criteria must be met:

- Normal knee stability (negative pivot shift test, ≤3 mm increase anteroposterior tibial displacement on Lachman test or knee arthrometer test)
- Full ROM
- ≤15% deficit peak torque hamstrings and quadriceps on isokinetic test (180°/s and 300°/s)
- ≤15% deficit in the distance hopped between the reconstructed and contralateral legs on single-leg hop for distance and single-leg triple hop for distance tests
- Successful completion of running program with no pain, swelling, or giving way
- Successful completion of basic plyometric training with therapy staff

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. 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. The following is the recommended protocol for implementation of the home-based program:

1. The physical therapist or trainer meets with the 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 the patient meet the next week, and the patient demonstrates jumps. If done correctly, training begins. The patient completes phase 1 over the 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 patient has mastered jumps in phase 3.

Critical Points

- Sportsmetrics program.
- Criteria:
  - Normal knee stability
  - Full range knee motion

  - ≤15% deficit isokinetic peak torque quadriceps, hamstrings
  - ≤15% deficit in distance hopped on single-hop leg, single-leg triple hop
  - Successful completion running program
  - Successful completion basic plyometric training
- Continue strengthening, other rehab exercises.
- Prefer training accomplished with therapist, certified trainer.
- Training may be done with videotape, with therapist involved at the beginning of each of the three stages of training for technique instruction.
- Extra time may be required to complete each phase of training.

22.2.7 Release to Unrestricted Sports Activities

Return to sports activities is based on successful completion of the running and functional training/plyometric programs and the following criteria (Fig. 22.17) [20, 41]:

1. Knee examination
   (a) ROM: International Knee Documentation Committee (IKDC) rating of normal or nearly normal
   (b) Lachman test: IKDC rating of normal or nearly normal
   (c) Pivot shift test: IKDC rating of normal or nearly normal
   (d) Patella pain: none
   (e) Effusion: none
2. KT-2000 [42, 43]
   (a) ≤3 mm reconstructed—contralateral knee (if normal), 134 N total AP displacement
3. Quadriceps and hamstrings muscle strength and endurance tests: ≤10% deficit compared with contralateral side, based on equipment available:
   (a) Isokinetic 180°/s and 300°/s [44–54]
   (b) Isometric portable fixed or handheld dynamometer: quadriceps 60° flexion, hamstrings 60° or 90° flexion, three reps each, use average [55–57].
   (c) If isokinetic or isometric equipment is not available, a one-repetition maximum bench press and leg press are recommended with weight room equipment, along with an experienced test administrator and a sufficient amount of time to safely conduct these tests [58, 59].
4. Single-leg hop tests: ≤15% deficit lower limb symmetry on any two tests (single hop, triple hop, triple crossover hop, timed hop) [46, 50, 54, 60–64]. May videotape to provide subjective analysis of balance and landing position.
5. Video drop-jump [65–68]:
   (a) If software is available, ≥60% normalized knee separation distance.
   (b) If software is not available, use video for subjective analysis of landing position (varus, valgus, neutral): no valgus, knees flexed for controlled landing.
6. Single-leg squat, five reps: no knee valgus, medial-lateral movement, or pelvic tilt [69–72]
7. Video plant and cut drill: subjective rating of high hip and knee flexion, upright posture, no valgus collapse [73–75]. This test should be done in the manner described by Pollard and associates [76] where the patient runs 5 m to a spot designated on the floor with tape, plants on the reconstructed 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°.

Other tests to consider before the patient is released to unrestricted athletic activities include the multistage fitness test to estimate VO_2max [77] and the 60-s sit-up test or other core strength measures [78].

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-

Fig. 22.17 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

inflammatories, and use ice and elevation. 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.

Critical Points

- Criteria for return to unrestricted sports:
  - Successful completion 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-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 plant and cut drill

22.3 Protocol with Delayed Parameters for Revision ACL Reconstruction, Multi-Ligament Reconstruction, Allografts, and Complex Knees

We developed a postoperative rehabilitation protocol (Table 22.8) for patients who undergo ACL revision, ACL allograft (primary or revision) reconstruction, 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 damage. 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. Toe-touch-only weight bearing is allowed for the first 2 postoperative weeks. The amount of weight patients are allowed after this time 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 and 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 patients placed in this protocol, 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. Knees that undergo a posterolateral reconstructive procedure are placed into a bivalved long-leg cast for the first 4 weeks [79]. 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 [80] or complex meniscus repair [81, 82].

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 activity 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

Table 22.8 Cincinnati Sportsmedicine and Orthopaedic Center rehabilitation protocol for ACL reconstruction: revision knees, allografts, complex knees

	Postoperative weeks					Postoperative months			
	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, sport-specific drills									(X)
Full sports									(X)

BAPS Biomechanical Ankle Platform System, *BBS* Biodex Balance System Running, agility training, plyometric training, full sports: (X) based on symptoms, condition of the articular cartilage, and isokinetic testing goals, see text

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 the 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.

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23

Restoration of Proprioception and Neuromuscular Control Following ACL Injury and Surgery

Kevin E. Wilk

Abstract

This chapter summarizes current rehabilitation strategies required to restore normal muscle strength, joint function, and neuromuscular control after ACL injury and reconstruction. A summary of the effects of ACL injury on proprioception, gait, and neuromuscular control is provided. A comprehensive neuromuscular training program is described that includes balance, perturbation, plyometric, and technique training. The authors' successful postoperative rehabilitation program is presented in detail.

23.1 Introduction

Proprioception plays a vital role in preventing and treating ACL injuries. It has been estimated that there are 200,000 ACL injuries sustained annually in the USA. Wilk [1] reported that approximately 148,714 ACL surgeries are performed in the USA annually according to insurance data information. Most ACL injuries are sustained from noncontact mechanisms that may occur on a jump-land deceleration or from a twist while running and cutting during sports. The proper and thorough rehabilitation of ACL injuries in active patients must include proprioception and neuromuscular control exercises.

Following ACL injury, it has been thoroughly documented that the injured individual will exhibit diminished proprioception and control for several months [2–4]. Furthermore, it was recently reported that a significant amount of ACL patients exhibit kinesiophobia [5, 6]. This fear of reinjury may be due, in part, to compromised proprioception and neuromuscular control. Fitzgerald et al. [7] reported that a rehabilitation program for ACL deficits which emphasized proprioception and perturbation training allowed a higher return to activity than a program that emphasized ROM and strength. Thus, a thorough well-designed ACL rehabilitation program must include proprioception, neuromuscular drills, and perturbation training to successfully return the patient to high-level activities and reduce the incidence of kinesiophobia.

23.2 Terminology

The terms proprioception, kinesthesia, and neuromuscular control are often used interchangeably; however, each has a unique definition. Proprioception represents the sense of awareness of the joint position, whereas kinesthesia describes the sensation of joint movement [8]. Wilk [9] defined neuromuscular control as the

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afferent sensory recognition of joint position and the efferent response to that awareness. Neuromuscular control provides the functional component referred to as dynamic stabilization. Perturbation is defined as a postural disturbance. Thus, perturbation training includes postural disturbance training drills.

Proprioception is accomplished by a sensory pathway response that is triggered by mechanoreceptors within the synovial joints. These mechanoreceptors include pacinian corpuscles, Ruffini endings, muscle spindles, and Golgi-tendon organs (GTO) which are located in muscles, capsules, and ligaments. These components work together to transmit sensory information regarding joint position, movement, and strain using afferent pathways to the central nervous system (CNS). In response, the CNS relays electrical signals via efferent pathways to corresponding muscles surrounding the joint to change muscle joint tone and function.

The joint and muscle receptors have important roles in the transfer of extrinsic muscle stiffness [10] and thus contribute to dynamic joint stability. Receptors in muscles contribute to muscle stiffness through either force feedback, which is altered by the GTO [11], or length feedback, which is mediated by the muscle spindle pathway which facilitates motor activity [12, 13].

Furthermore, two additional mechanisms have been hypothesized for the joint receptors' contribution to joint stability. The first mechanism is a direct ligamentous-muscular protective reflex as in, for example, the reflex between the ACL and hamstring muscles. When tension is generated onto the ACL, the mechanoreceptors are stimulated resulting in a reflex inhibition of the quadriceps and facilitation of the hamstring muscles. This response protects against increasing strain on the ACL. The second proposed mechanism is the indirect contribution of the joint receptors to dynamic joint stability. In this proposal, referred to as presetting [14], the joint receptors contribute to preparatory adjustments of muscle stiffness. The author believes the concept of presetting is critical in providing joint stability during functional activities such as preparing to decelerate, performing a cutting maneuver, or landing from a jump.

Motor responses are dependent on the level of processing of afferent inputs within the CNS, which may occur at the spinal cord, the brainstem, or the cerebral cortex [15]. The site of processing influences the speed of motor responses. The shortest neuronal pathways, and consequently the most rapid response to afferent stimuli, are located in the spinal cord. These spinal reflexes are believed to be faster than ligament failure. Alternatively, sensory information originating at the brainstem, cerebellum, and cortical levels involve longer pathways and thus, slower response times. Numerous studies [16–18] have reported that neuromuscular training can affect the sensory input processed at the CNS above the spinal cord level. Therefore, due to the adaptability of the responses at the brainstem and the cerebellum, these pathways may be important in providing dynamic knee stability [19].

ACL injuries may disrupt the complex interactions within the neuromuscular system, resulting in diminished proprioception and kinesthesia, abnormal patterns of muscle activity [20], and reduced dynamic joint stability [21–23]. An ACL injury to one knee may in addition affect the proprioception on the opposite lower extremity [4, 24] and decrease muscle strength in the opposite quadriceps muscle [25–27]. Therefore, as soon as possible after the injury, the rehabilitation program must create an environment that promotes the restoration of motor responses and proprioception for both extremities.

There are other terms that require classification. Open-loop control is a movement that is brief, predictable, and produced in an unchanging environment which does not require sensory information for modification. Thus, these movements do not require feedback [18]. Conversely, closed-loop control movements rely on feedback from the sensory system.

Motor skills have been defined with respect to the environment by Chmielewski et al. [28]. Closed motor skills are those performed in a relatively stable environment such as walking, stair climbing, and extending the leg. Open skills are performed in an environment which is changing and unpredictable such as running in the woods, downhill skiing, or balancing on a wobble board.

Sports such as basketball, soccer, and football represent open skill activities, as they depend on the ability of the individual to react to a joint position or a perturbation.

Critical Points

- Proprioception: sense of awareness of the joint position.
- Kinesthesia: sensation of joint movement.
- Neuromuscular control: afferent sensory recognition of joint position and the efferent response to that awareness provide dynamic stabilization.
- Motor responses depend on level of processing of afferent inputs within CNS. Processing may occur at spinal cord, brainstem, or cerebral cortex. Sensory input processed at CNS above spinal cord level may be altered with neuromuscular training.
- Perturbation: postural disturbances.
- ACL injuries may disrupt interactions within neuromuscular system, resulting in diminished proprioception and kinesthesia, abnormal patterns of muscle activity, and reduced dynamic joint stability.
- An ACL injury to one knee may affect the proprioception and muscle strength in the opposite lower extremity.

23.3 Effects of ACL Injury on Proprioception

Several investigations reported a decrease in proprioception and kinesthesia following ACL injury [21, 22, 24, 29, 30]. After ACL injury, deafferentization of peripheral sensory receptors occurs [30, 31], causing rapid alterations in proprioception. Lephart and associates [8] reported that changes in proprioception may occur within 24 h of ACL injury. Alterations in proprioception may persist for 1–2 years after surgery [32–34].

Following an injury, changes occur within the joint that influence normal recruitment and timing patterns of the surrounding musculature [35]. There are several theories to explain this deterioration of musculature activation. One theory relates to an alteration in the ratio of muscle spindle to GTO activity, leading to interruption of the proprioception pathway. Joint effusion following an acute injury may affect the ability of the muscles to contract, which leads to decreased proprioception. Palmieri-Smith et al. [36] found that a joint effusion of just 30 ml significantly decreased the activation of the vastus medialis and lateralis muscles on a single-leg drop landing. This amount of joint effusion is barely palpable by the clinician.

ACL injuries may lead to significant limitations for athletes. Wojtys and Huston [4] reported a significant decrease in muscle activation timing and recruitment order in the medial and lateral quadriceps, medial and lateral hamstrings, and gastrocnemius in response to an anterior tibial translation in a group of ACL-deficient knees compared to controls. The authors postulated that this delay in muscle recruitment may lead to decreased joint stability because, as a result of the injury, the musculature becomes the prime joint stabilizer instead of the ACL. Beard et al. [22] applied 100 N of anterior shear force in ACL-deficient patients and reported a reflexive activation of the hamstring muscles occurred. Paterno et al. [37] found a significant difference in force production during a drop vertical jump a mean of 27 months after ACL reconstruction in the ACL-reconstructed knee compared to the contralateral limb. Many studies [4, 24, 33, 34, 37–39] have demonstrated differences exist between the ACL-reconstructed and opposite limbs for an extended period of time following surgery.

Hooks et al. [24] reported that, 24–48 h following ACL injury, proprioception was altered bilaterally as measured on a stability system. Following ACL injuries, the uninvolved lower extremity's ability to stabilize on a sway board (Biodex Stability System, Shirley, New York) was compromised for 6–8 weeks, with a gradual improvement in sway balance returning after that time period.

23.4 Effects of ACL Injury on Gait

Studies have reported that some patients exhibit alterations in gait patterns following ACL injury.

The term "quadriceps avoidance gait pattern" was introduced by Andriacchi and Birac [2] and Berchuck et al. [40] in the 1990s. Patients with this gait abnormality walk with increased hamstring activity, a flexed knee, and minimal to no quadriceps electromyographic (EMG) activity. It has been the clinical observation of the author that these protective neuromuscular adaptations (quadriceps avoidance gait) may persist for many months following ACL injury if not appropriately addressed in the rehabilitation program.

23.5 Duration of Proprioception and Neuromuscular Deficits

The length of time that a patient with an acute injury to the ACL experiences a decreased sense of proprioception and neuromuscular control is unclear. The literature suggests 1–3 years as the time frame for altered proprioception of the ACL-deficient knee. Harrison et al. [41] measured differences between the ACL-reconstructed knees and uninvolved legs during single-leg stance in 17 patients who were 10–18 months post-surgery. The researchers found no significant differences in postural sway in these subjects with eyes both open and closed. These findings suggest that proprioception may be restored in a shorter time frame than what some authors have suggested.

Others suggest a longer period of time is required until proprioception and joint position sense are reestablished. Fremerey et al. [42] measured joint position sense at different time intervals after ACL reconstruction in 20 patients, comparing the data to information gathered before surgery. Joint position sense of the ACL-reconstructed knee was almost completely restored at near end ranges of knee flexion and knee extension 6 months postoperatively. However, proprioception at the midrange of knee motion was not fully restored at this time period. Some of the patients required over 3½ years to fully recover normal joint position sense at midrange knee motion position. This is concerning to athletes because a majority of activities that occur during competition do so at midrange of knee motion positions. The lack of joint position sense at these levels may increase the probability of a reinjury.

Another theory to consider when studying the duration of decreased proprioception in patients with acute ACL injury is the preinjury level of activity of the individual. Roberts et al. [43] reported an association between preinjury activity levels and time to regain normal joint position sense following ACL reconstruction, with high preinjury activity levels accelerating this process.

Critical Points

- Decrease in proprioception and kinesthesia occurs after ACL injury.
- Changes occur within the joint that influence normal recruitment and timing patterns of the surrounding musculature. Decrease in muscle activation timing and recruitment order.
- Patients with ACL-deficient knees may walk with increased hamstring activity, a flexed knee, and minimal to no quadriceps electromyographic activity.
- Literature suggests 1–3 years as the time frame for altered proprioception of the ACL-deficient knee.

23.6 Clinical Relevance

The rehabilitation program for ACL injuries must contain several components that are considered crucial for the safe and effective recovery of the athlete. One of these components is the restoration of neuromuscular control, which begins almost immediately following ACL reconstruction. The early emphasis on regaining neuromuscular control is to prevent deafferation of the knee joint. The progression of the patient must be increased gradually, and it is the duty of the therapist to carefully balance between a detrimental slow progression and an abundance of force from advanced exercises done prematurely in therapy that could have dangerous results. Additionally, the rehabilitation specialist must consider the other stresses that neuromuscular training places on the patient's joint and factor those stresses into the overall volume of work required of the patient. A delicate balance must be achieved to maximize rehabilitation benefits while preventing fatigue without recovery that could lead to problems or delays in recovery.

There are several techniques that the therapist can use early after injury or surgery that do not involve the ACL-injured knee. For instance, neuromuscular training may be performed on the contralateral extremity. It is possible to achieve a carry-over effect from training the uninvolved extremity, resulting in improvements in the injured side. The technique of passive-active joint repositioning, which may be performed immediately following surgery or injury, is valuable in restoring joint awareness. Another option is to challenge the core of the patient. When treating an athlete, it is ideal to challenge the core while the patient is in an athletic stance so it has the most relevance to the patient's sport. Core activities also help prepare the entire body to return to sports when the patient is ready for more strenuous activities. Core training may assist in reducing the incidence of ACL injuries.

Another important concept is to train the hip musculature to control femoral adduction and internal rotation. The goal is to stabilize the knee joint from "above and below" [44, 45]. It is important to control or minimize hyperpronation of the foot, thus controlling tibial internal rotation. Paterno et al. [46] reported that altered neuromuscular control of the hip and knee during landing task and postural deficits after ACL reconstruction may be factors among others for a second ACL injury.

23.7 Stages of Motor Skill Development

There are four stages of progressing when learning a new motor skill: mobility, stability, controlled mobility, and skill [47]. Mobility describes the available ROM required to obtain a posture or position, along with sufficient motor unit activity to initiate the movement. A movement or skill cannot be performed if an individual does not have adequate mobility. Stability describes the ability to produce a co-contraction to provide tonic holding. Controlled mobility refers to movement added to a stable posture, such as rocking back and forth, weight shifting, and balancing on an unstable platform. Skill, the highest level, refers to function and the ability to manipulate and perform tasks in an unstable environment, such as kicking a ball or hitting a ball with a racquet.

Chmielewski et al. [48] classified motor skill development into three stages: cognitive, associative, and autonomous. The cognitive stage refers to the time period when a new task or drill is introduced. During this stage of development, errors are made, movement is rigid or stiff, and more training is required for the individual to learn the new task. The associative stage involves less time spent thinking about the task or drill with the movement improved, but still not automatic. The autonomous stage describes the period when the movement, after practice, has become automatic and efficient and, with time, more skilled. In sports, skills such as shooting a basketball, hitting a tennis serve, or swinging a golf club are specialized skills requiring these three stages of motor development. In addition, the author has identified a fourth stage, referred to as the "refining stage," during which time the individual refines the task or drill to a level of perceived perfection.

Critical Points

- Restoration of neuromuscular control begins almost immediately following ACL injury or reconstruction.
- Conduct neuromuscular on opposite limb first.
- Passive-active joint repositioning of both limbs.
- Work the core. Stabilize the knee joint from "above and below."
- Four stages of learning a new motor skill: mobility, stability, controlled mobility, and skill.
- Three stages of motor skill development: cognitive, associative, and autonomous.

23.8 The Neuromuscular Training Program

A neuromuscular training program may be initiated by the clinician through a variety of training methods. The program should be multiphased, progressive in levels of difficulty, use both isolation and combined movements, and be adaptable (Table 23.1). The patient's own neuromuscular status, desired goals, and phase of the rehabilitation program must be taken under consideration (i.e., acute, subacute, advanced, or return-to-activity phase). Importantly, the individual must be challenged in order to make sufficient gains [49, 50]. When learning a new skill or task, a 50–60% failure rate needs to occur to enhance neuromuscular control and improve dynamic stability.

Based on these basic science principles, a four-phased rehabilitation program will be presented in this chapter which emphasizes proprioception and neuromuscular training. There are numerous training techniques that may be used in each phase, several of which will be briefly described. Of interest, Distefano et al. [51] reported that young athletes (under 12 years of age) can improve balance and vertical jumping height following neuromuscular training. This type of training, noted to be a crucial factor in ACL injury prevention in adolescents and adults, may be essential for prepubescent children as well.

It is important to note that the very early return to running, plyometrics, and athletics is not recommended in patients who undergo associated operative procedures such as a complex meniscal repair, other ligament reconstruction, patellofemoral realignment, articular cartilage restorative procedure, or osteotomy. Additionally, patients who have a major bone bruising or articular cartilage damage are also not candidates for the early return

Table 23.1 Proprioception and neuromuscular drills

Drill	Options
Stability position drills (knee flexed to 30°–45°, hip flexed to 30°–45°)	Standing on floor Standing on floor, eyes closed Standing on floor catching ball Standing on floor with weighted ball going up and down Standing on foam Standing on foam ball catches Standing on foam with weighted ball overhead side-to-side movements
Stepping drills	Stepping over cones or cups Forward and backward Side step-overs Speed drills (slow, fast, slow) Stepping over with ball catches Stepping over cone onto foam Step over huddle with rotation
Lateral lunges	Straight lateral without cord Straight lateral with cord Diagonals at 30° angles Diagonal with rotation Straight lateral onto foam Lateral fast movements Lateral lunges with ball catches Lateral lunges onto rocker board
Unilateral deadlifts (RDLs)	Unweighted Weighted Weighted with shoulder flexion and trunk extension
Hip abduction and hip external rotation	Clams RDLs Star Side plank Side plank with hip abduction Side plank with hip abduction against wall Side plank with hip against wall with Theraband

Table 23.1 (continued)

Drill	Options
Bridging	Bilateral bridging Unilateral bridging Bridging on stability ball Stability ball with Theraband Floor bridging with hip abduction Floor bridging with manual resistance
Perturbations	Tilt board squats Tilt board squats with ball catches Tilt board squats with catches and perturbation Single-leg stability position (knee) with ball catches BOSU ball squats BOSU ball squats with ball catches Stance on foam with ball and perturbations
Step-downs (single leg)	Step-downs on floor Step-downs off box Step-downs with Theraband resistance Step-downs with ball catches Step-downs on foam with ball catches Step-downs on foam with Theraband and ball catches Step-downs with perturbations
Ladder agility drills	2 feet chops forward 2 feet chops side Front foot in and out lateral Back foot in and out lateral Icky shuffle Combination drills Combination drills with reverses Ladders with Theraband CLX
Vertical drop jump/landing	2-legged jump on ground 2-legged jump off box 2-legged jump bounding forward 2-legged side jumps 2-legged side jumps off box 2-legged jumps onto foam 1-legged jumps on floor

to strenuous activities. For all of these patients, delays are built into the postoperative protocol for full weight bearing, certain strengthening and conditioning exercises, running and agility drills, plyometrics, and return to full sport activities.

23.8.1 Joint Repositioning

Lephart et al. [8, 23] introduced this technique which begins with passive joint positioning, followed by requesting the patient to actively reposition their knee joint angle to the beginning position. This is referred to as passive, then active, joint repositioning (Fig. 23.1). This technique may be performed as either a test of proprioception or as a rehabilitation training technique following ACL injury or surgery.

23.8.2 Balance Training

Balance training exercises are used to expedite the proprioceptive component of postural control and to reduce postural sway. This training may be performed on the floor or on an unstable surface such as foam or air mattresses. An unstable surface is preferred when the patient is able because it increases the neuromuscular challenge. Balance training may also be done with a balance training device (Fig. 23.2) or on a force platform to determine the patient's weight distribution (Fig. 23.3). Available devices include wobble boards (Fig. 23.4), rocker boards (Fig. 23.5), and the Biodex Stability System (Biodex Medical Systems, Shirley, NY).

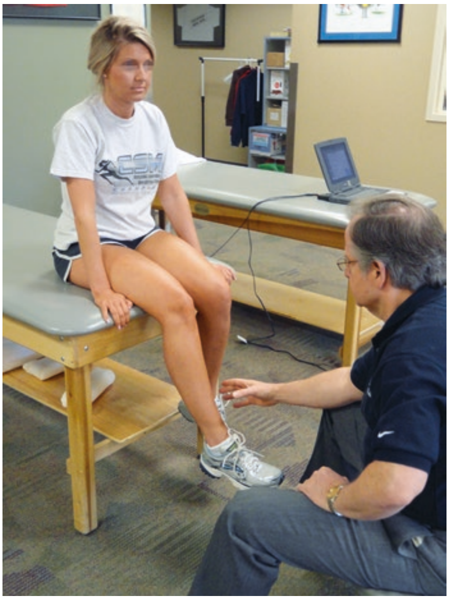

Fig. 23.1 Passive then active joint repositioning drill. The patient's lower extremity is placed at a measured range of motion by the clinician. The clinician then returns the lower extremity to the rest position and asks the patient to actively position the lower extremity in the same position that the clinician placed it in previously

Fig. 23.2 The Biodex Stability System may be used for a variety of tests or rehabilitation drills. The author uses this device in balance as well as perturbation training

Fig. 23.3 Balance training done on a force platform so that the patient receives visual feedback regarding the amount of weight distribution between the lower extremities

Fig. 23.4 Wobble board used for balance training drills

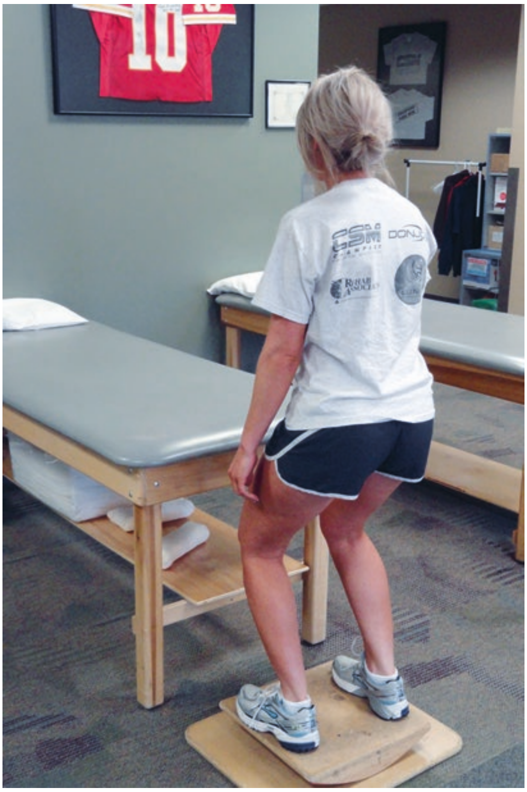

Fig. 23.5 Rocker boards used for balance training and perturbation training drills

23.8.3 Perturbation Training

Perturbation training entails a reactive motor response to a change in postural position. An applied force is used by the clinician to create a postural disturbance. For example, a patient steps on a rocker board and assumes a single-limb stance, and then the clinician applies an external force (either by tapping the board or the individual) which creates a disturbance, requiring the patient to react to the stimulus and correct the postural change. Perturbation training should progress from easy to advanced challenges. Low-level perturbations are predictable, small in force, and unchallenging. On the contrary, as changes in posture increase in load, speed, and force, this exercise becomes more difficult and progresses from single-plane to multi-plane challenges.

Wilk et al. [52] introduced perturbation training in the ACL-injured female athlete in 1996. Later, Wilk et al. [53] emphasized this form of training as a "critical component" for athletes to master to enable the successful return to athletic activities. Fitzgerald et al. [7] reported that perturbation training resulted in improved outcomes in ACL-deficient knee patients in regard to return to sports. Wilk and associates [45, 52–54] and Snyder-Mackler et al. [55] strongly recommended this form of training for ACL rehabilitation. In ACL-deficient knees, Chmielewski et al. [20, 28] reported that perturbation training enhanced the restoration of knee joint kinematics and a reduction in quadriceps-hamstring muscle co-activation. Hurd et al. [56] reported that perturbation training enhanced neuromuscular training and improved muscle activity and dynamic stability in female athletes.

Recently discovered effects on the human body following ACL injury are neuroplasticity pathways and synapses of the young brain and nervous system in response to the experience of injury. Grooms et al. [57] demonstrated that neuroplasticity occurs in humans following ACL injury. Specific rehabilitation strategies are available to treat these effects, including dual tasking, visually impaired rehab techniques, stroboscopic glasses, and other visual elements.

23.8.4 Plyometric Exercises

Plyometrics is a term that commonly refers to jump training or stretch-shortening exercise drills. Wilk et al. [54] described plyometric training as "reactive neuromuscular training." These exercises are generally used to enhance athletic performance, assist athletes in preparation for return to sports during the advanced phase of rehabilitation, and in ACL injury prevention training programs. Studies [58–60] have shown that a well-designed plyometric program can reduce the incidence of ACL injuries in the female athlete (see Sect. III).

Plyometrics use the stretch-shortening cycle of muscle contraction whereby the stretch cycle elicits an eccentric contraction and the shortening cycle creates a concentric contraction. Importantly, plyometric training of the lower extremity should focus on proper techniques and body position mechanics, with the goal of reducing the risk of serious injury. For instance, correct upper body and knee positions are critical during the landing phase of plyometric drills. The athlete should land in deep knee flexion and focus on controlling the valgus movement of the knee joint. In addition, the athlete should be taught to land with an abducted and externally rotated hip to help prevent a valgus collapse of the knee joint. Durall et al. [61] recently reported that athletes with a decreased postural control had a higher hip abduction moment and a more extended hip on landing in female athletes. Noyes et al. [62] and Barber-Westin et al. [63] suggested using a video drop-jump test to detect a lower-limb valgus position on landing. Lower extremity plyometrics are progressed from double-leg drills to single-leg drills and jumps from the ground to jumps off a box and may also entail catching a ball or using resistance cords.

23.8.5 Technique Training

Technique training involves sport-specific or performance training with an emphasis on proper technique. These types of drills include running and cutting, deceleration while running, pivoting, and landing from a jump. The clinician should offer both verbal and visual feedback to the patient. Cues including "land light as a feather," be a "shock absorber," and act as a "spring" are helpful [64]. Technique training reduced the incidence of ACL injury in one study [65]. Proper technique during soccer-specific maneuvers described by Mandelbaum et al. [60] in their ACL preventative program helped to significantly reduce ACL injuries. The Sportsmetrics program emphasizes proper landing from plyometric jumps and also teaches correct form for cutting and pivoting [64, 66]. In this training program, athletes who fail to perform a jumping exercise correctly are stopped, and the technique is demonstrated again by the instructor and practiced until the desired landing technique is demonstrated. Myer et al. [67] reported that plyometrics and balance training are effective in improving neuromuscular control. Myer et al. [68] reported that balance and plyometric training can reduce the valgus moment at the knee joint.

23.8.6 Psychosocial Factors and Reinjury

Patients with knee osteoarthritis appear to have better outcomes if they exhibit positive attitudes and coping skills. Several studies have examined the psychosocial factors related to the ACL patient. Chmielewski et al. [69] reported that pain was consistently associated with function across time frames following ACL reconstruction. Furthermore, fear of movement or reinjury was reported to gradually decrease during the rehabilitation program.

Kinesiophobia is the fear of movement or reinjury. This term was first described by Woby et al. [70] as it related to low back patients. Later, Chmielewski et al. [5, 69] applied the term and the disorder to ACL-injured patients. There are numerous factors which may contribute to kinesiophobia. In this author's opinion, one way of reducing this disorder is to build neuromuscular confidence through proprioception, neuromuscular, and perturbation training drills.

Chmielewski et al. [5] reported interventions that increased self-efficacy or decreased fear of movement resulted in an improvement in outcomes. The program discussed in this chapter is designed to improve limb confidence through a progression of neuromuscular drills and challenges. Each phase builds on the previous and is designed to improve proprioception, neuromuscular control, and function. The author strongly believes that limb confidence is an important component required to successfully return an individual back to preinjury function.

Critical Points

- Neuromuscular training program should be multiphased, be progressive in levels of difficulty, use both isolation and combined movements, and be adaptable. The patient's own neuromuscular status, desired goals, and phase of the rehabilitation program must be taken under consideration.

- Techniques: joint repositioning, balance training, perturbation training, plyometric training, and sport-specific or performance training.
- Patients with knee osteoarthritis appear to have better outcomes if they exhibit positive attitudes and coping skills.

23.9 The Preoperative Rehabilitation Program

Before ACL reconstruction is performed, there are important goals for the patient to achieve in order to prepare for the operation. The restoration of normal knee motion (especially extension) and voluntary muscle activation; resolution of inflammation, swelling, and pain; and education of the patient regarding the postoperative rehabilitation process are critical components for a successful overall outcome. The knee is protected from further injury, especially to the menisci. An elastic wrap or knee sleeve may be used to reduce swelling, and weight bearing is allowed with or without crutches as tolerated. The patient performs ankle pumps, passive knee extension to 0°, passive knee flexion to tolerance, straight leg raises in three planes (flexion, abduction, adduction), quadriceps sets, mini-squats, lunges, and step-ups.

Electrical muscle stimulation may be used to stimulate the quadriceps during voluntary quadriceps exercises for 4–6 h per day. Cryotherapy may be used for 20 min every hour if required. The leg is elevated as often as possible with the knee in full extension and with the knee above the heart. Neuromuscular and proprioception exercises include gait training to eliminate a quadriceps avoidance gait, retro stepping drills, and balance training drills. The postoperative rehabilitation is reviewed with the patient so they are prepared for the operation.

23.10 The Postoperative Rehabilitation Program

Our rehabilitation program following ACL bone-patellar tendon-bone autograft reconstruction is shown in Tables 23.2, 23.3, and 23.4. Neuromuscular training drills are integrated into the program and may begin the day following ACL surgery. These drills are progressed from simple to complex, isolated to combined, and blocked to random. Blocked training refers to a particular component of a skill, with each component practiced before progressing to the next. Conversely, random training entails different skills practiced interchangeably throughout a practice session. During the training, external feedback is given to the athlete in the form of instructions, technique guidance, and examples. Occasionally, the athlete receives visual feedback from mirrors, videotaping, or a force pattern. These techniques aid in technique modification and mastering a specific movement drill. The program is based on 11 key components:

1. Immediate stimulation of mechanoreceptors following injury and/or surgery.
2. Stimulate mechanoreceptors of contralateral extremity.
3. Facilitate co-contraction to enhance dynamic stability (immediately).
4. Control the knee from above and below (through the hip and foot/ankle).
5. Establish early core stability (restore trunk proprioception/stability).
6. Establish posterior chain control and strength.
7. Perturbation training to enhance neuromuscular control.
8. Train to improve endurance.
9. Challenge the neuromuscular system.
10. Gradually increase challenges to the neuromuscular system.
11. Neuromuscular training never stops; enhancement continues for years.

The four-phased neuromuscular training program is shown in Table 23.4. This chapter briefly discusses examples of drills in each phase of the rehabilitation program.

23.10.1 Phase I: Acute Phase Drills

A variety of neuromuscular training drills and activities may be initiated immediately following

Table 23.2 Rehabilitation program following ACL bone-patellar tendon-bone autograft reconstruction[a]

Phase, postoperative day	Goals	Brace, weight bearing, range of motion	Exercises	Modalities	Neuromuscular, proprioception training
Phase 1 Day 1	Restore full passive knee extension Diminish joint swelling, pain Restore patellar mobility Gradually improve knee flexion Reestablish quadriceps control Restore independent ambulation	Brace or immobilizer, knee locked in full extension during ambulation, sleeping; unlocked while sitting. 2 crutches, weight bearing as tolerated	Ankle pumps Overpressure into full, passive knee extension Active, passive knee flexion (90° by day 5) Straight leg raises (flexion, abduction, adduction) Quadriceps isometric setting Hamstring stretches Closed kinetic chain exercises: mini-squats, weight shifts	EMS during active muscle exercises (4–6 h per day) Continuous passive motion as needed, 0–45–50° (as tolerated, directed by physician) Ice 20 min every hour Elevate with knee in full extension	
Phase 1 Days 2–3	Same	Brace or immobilizer, locked at 0° extension for ambulation, unlocked for sitting. 2 crutches, weight bearing as tolerated. ROM: remove brace, perform 4–6 times per day	Multi-angle isometrics (90°, 60°) Knee extension (90–40°) Overpressure into extension (knee extension at least 0° to slight hyperextension) Patellar mobilization Ankle pumps Straight leg raises (three directions) Mini-squats, weight shifts Quadriceps isometric setting	EMS 6 h per day Continuous passive motion as needed, 0°–90° Ice 20 min every hour Elevate with knee in full extension	
Phase 1 Days 4–7	Same	Brace or immobilizer, locked at 0° extension for ambulation, unlocked for sitting. 2 crutches, weight bearing as tolerated ROM: remove brace, perform 4–6 times per day, knee flexion 90° by day 5, 100° by day 7	Multi-angle isometrics (90°, 60°) Knee extension (90–40°) Overpressure into extension (extension 0° to 5–7° hyperextension) Patellar mobilization (5–8 times daily) Ankle pumps Straight leg raises (3 directions) Mini-squats, weight shifts Standing hamstring curls Quadriceps isometric setting	EMS 6 h per day Continuous passive motion as needed 0°–90° Ice 20 min every hour Elevate with knee in full extension	OKC passive-active joint repositioning 90°, 60° CKC squats, weight shifts with repositioning

Phase II Week 2	Maintain full passive knee extension (at least 0° to 5°–7° hyperextension) Gradually increase knee flexion Diminish swelling, pain Promote muscle control, activation Restore proprioception, neuromuscular control Normalize patellar mobility	Continue locked brace for ambulation, sleeping Weight bearing as tolerated (goal discontinue crutches 10–14 days post-op) PROM: self-ROM stretching (4–5 times daily), emphasis on maintaining full, PROM	Muscle stimulation to quadriceps exercises Isometric quadriceps sets Straight leg raises (four planes) Leg press (0–60°) Knee extension (90–40°) Half squats (0–40) Weight shifts Front and side lunges Hamstring curls standing (active ROM) Bicycle (if ROM allows) Overpressure into extension PROM 0–100° Patellar mobilization Well-leg exercises Progressive resistance extension program: start with 1 lb, progress 1 lb per week	Swelling control—ice, compression, elevation	OKC passive-active joint repositioning 90°, 60°, 30° CKC joint repositioning during squats and lunges Initiate squats on tilt board
Phase II Week 3	Same	Discontinue locked brace (may use ROM brace for ambulation). If patient continues to use brace, unlock for ambulation. PROM: continue ROM stretching, overpressure into extension (ROM should be 0–100/105°)	Continue all exercises from week 2 PROM 0–105° Bicycle for ROM stimulus, endurance Pool walking (if incision is closed) Eccentric quadriceps 40°–100° (isotonic only) Lateral lunges (straight plane) Front step-downs Lateral step-overs (cones) Stair stepper machine	Same	Continue passive, active reposition drills (CKC, OKC)

(continued)

Table 23.2 (continued)

Phase, postoperative day	Goals	Brace, weight bearing, range of motion	Exercises	Modalities	Neuromuscular, proprioception training
Phase III Weeks 4–5	Restore full ROM (5–0–125°) Improve lower extremity strength Enhance proprioception, balance, neuromuscular control Improve muscular endurance Restore limb confidence, function	Brace—discontinue, may use knee sleeve to control swelling, add support ROM: self-ROM (4–5 times daily using the other leg to provide ROM), emphasis on maintaining 0° passive extension PROM 0–125°	Progress isometric strengthening program Leg press (0°–100°) Knee extension (90°–40°) Hamstring curls (isotonics) Hip abduction-adduction Hip flexion-extension Lateral step-overs Lateral lunges (straight plane and multi-plane drills) Lateral step-ups Front step-downs Wall squats Vertical squats Standing toe calf raises Seated toe calf raises Biodex Stability System for balance, squats Bicycle Stair stepper machine Pool program (backward running, hip and leg exercises) Unloaded treadmill walking		Tilt board squats (perturbation) Passive-active reposition OKC CKC repositioning on tilt board
Weeks 6–7	Same		Continue all exercises Pool running (forward), agility drills Balance on tilt boards Progress to balance and ball throws Wall slides, squats		
Weeks 8–9	Same		Continue all exercises from weeks 4–6 Leg press sets (single leg) 0°–100°, 40°–100° Plyometric leg press Perturbation training Isokinetic exercises (90°–40° (120°–240°/s) Walking program Bicycle for endurance Stair stepper machine for endurance Biodex Stability System		Training on tilt board

Week 10	Same		Continue all exercises from weeks 6, 8, and 10 Continue stretching drills Progress strengthening exercises		Progress neuromuscular training
Phase IV Weeks 11–13	Normalize lower extremity strength Enhance muscular power and endurance Improve neuromuscular control Perform selected sport-specific drills		May initiate running program (weeks 10–12, physician decision) May initiate light sport program (golf, physician decision) Continue all strengthening drills: Leg press Wall squats Hip abduction-adduction Hip flexion-extension Knee extension 90°–40° Hamstring curls Standing toe calf raises Seated toe calf raises Step-downs Lateral step-ups Lateral lunges Plyometric leg press		Lateral step-overs (cones) Lateral lunges Tilt board drills
Phase IV Weeks 14–16	Same		Progress program Continue all drills above May initiate lateral agility drills Backward running		
Phase V Weeks 17–22	Gradual return to full-unrestricted sports Achieve maximal strength and endurance Normalize neuromuscular control Progress skill training		Continue strengthening exercises Progress running, agility programs Progress sport-specific training Running/cutting/agility drills Gradual return to sport drills		Continue neuromuscular control drills Continue plyometric drills

[a] See Table 23.3 for criteria to advance from one phase to the next

ROM range of motion, *EMS* electrical muscle stimulation, *OKC* open kinetic chain, *CKC* closed kinetic chain, *PROM* passive range of motion

Table 23.3 Criteria to advance in the rehabilitation program following ACL bone-patellar tendon-bone autograft reconstruction

Phase	Criteria
From I to II	Quadriceps control (ability to perform good quadriceps set and straight leg raise) Full passive knee extension PROM: 0°–90° Good patellar mobility Minimal joint effusion Independent ambulation
From II to III	Active ROM: 0°–115° Quadriceps strength: >60% contralateral side (isometric test 60° knee flexion) KT-2000 test (67 N total AP): within 2 mm of contralateral side Minimal to no full joint effusion No joint line or patellofemoral pain
From III to IV	AROM: ≥0°–125° Quadriceps strength: 75% of contralateral side Knee extension flexor: extensor ratio, 70–75% KT-2000 test (89 N total AP): within 2 mm of contralateral side No pain or effusion Satisfactory clinical exam Satisfactory isokinetic test (180°/s): Quadriceps: 75% of contralateral side Hamstrings: equal to contralateral side Quadriceps peak torque/body weight: 65% (males), 55% (females) Hamstrings/quadriceps ratio: 66–75% Single-leg hop test: 80% of contralateral leg Subjective knee scoring (modified Noyes system): ≥80 points
From IV to V	Full ROM KT-2000 test (134 N total AP): within 2.5 mm of contralateral side Isokinetic test that fulfills criteria: Quadriceps bilateral comparison: ≥80% Hamstring bilateral comparison: ≥110% Quadriceps torque/body weight ratio: ≥55% Hamstrings/quadriceps ratio: ≥70% Proprioceptive test: 100% of contralateral leg Single-leg hop test: ≥85% of contralateral side Satisfactory clinical exam Subjective knee scoring (modified Noyes system): ≥90 points
6 and 12 months post-op	KT-2000, isokinetic, and functional tests to fulfill required criteria (if required) before return to full activities

PROM passive range of motion, *ROM* range of motion, *AROM* active range of motion, *KT* knee arthrometer

ACL injury or surgery. During this time, the majority of drills are isolated and a blocked-training technique is used. Passive ROM exercises are beneficial in recovering joint position sense because they stimulate the mechanoreceptors. Passive-active reposition sense techniques may be done (with the patient's eyes closed) by the therapist to improve proprioception. Weight-bearing exercises are also safe and beneficial. Mini-squats (0°–40°) may be performed. If a force platform is available, this exercise may be done on the device to provide visual feedback to the patient regarding weight distribution (Fig. 23.6). Weight shifting may also be done on the force platform.

Gait retraining activities are begun during the second postoperative week. An example of one exercise is stepping over cones which may be done either laterally or forward and backward (Figs. 23.7 and 23.8). Electrical muscle stimulation (Emi Medical, St. Paul, Minnesota) to the quadriceps (Fig. 23.9) is strongly advocated as soon as possible following the injury or surgery to prevent quadriceps shutdown and assist in muscle reeducation, hypertrophy, and strength gains [71].

Table 23.4 Neuromuscular control drills

Phase	Drills
I	PROM flexion, extension
	Passive-active joint positioning: 90°, 60°, 30°
	Standing weight bearing
	Mini-squats on force platform
	Weight shifts force platform
	Knee sleeve
	EMS to quadriceps
	Quadriceps sets
	Straight leg raises: flexion
	Hip abduction, adduction
	Multi-angle isometrics: 90°, 60°, 30°
	Leg press 0°–100°, 0°–45°
	Leg press (Monitored Rehab Systems Leg Press, Fort Worth, Texas)
	Tilt board squats
	Cone stepping
	Lateral lunges no cord
	Biodex squats
	Quadrant stepping
	Mini-squat on foam
	Mini-squat on air mattress
	Rubber band around hip walking
	Wall slides 0°–60° (5°–7 s hold)
II	Continue selected drills and activities from phase I
	Lateral lunges with cord:
	Onto involved side
	Onto uninvolved side
	30° diagonal
	30° diagonal with rotation
	Lateral lunges:
	Straight with ball catches
	Diagonal with ball catches
	Onto foam
	Straight foam with rotation
	Straight foam with rotation with ball catch
	Standing:
	Up and down with ball (stability position)
	Balance position up and down with foam
	Dynamic stability position (knee 30° flexion, hip 30–45° flexion) on foam
	Single-leg, plyoball touching cones
	Front step-downs:
	On foam
	On foam ½ circle foam
	On foam with Theraband
	Lateral step-down with sport cord around waist
	BOSU balance squats
	Squats on rocker board
	Front lunge onto box
	Front lunge on foam
	Wall slides with physioball
	Single-leg wall slide
	Single-leg wall slides on a box
	Hip external rotation and internal rotation with tubing
	Sidelying clams
	Intrinsic foot exercise (towel gathering, marbles)
	Theraband inversion and eversion

(continued)

Table 23.4 (continued)

Phase	Drills

III	Continue selected drills and activities from phase II
	Single-leg squats with ball catch and touch cones
	Lateral lunge:
	  Diagonal slight jump
	  Diagonal slight jump with ball catch
	  Onto tilt board (stabilize)
	  Onto tilt board with ball catch
	Tilt board dynamic stability position (knee 30° flexion, hip 30–45° flexion):
	  With perturbation
	  With perturbation and ball catch
	  With perturbation and rotational throws
	Biodex squats:
	  With perturbation
	  With ball catch
	Lateral lunge:
	  Onto tremor
	  Onto tremor with ball catch
	Front jump lunge:
	  Onto tremor
	  Onto tremor with ball catch
	  Onto tremor with taps
	Side to side and up and down on tremor ball catch
	Plyometric leg press:
	  Straight
	  Side to side
	  Four corners
	BOSU ball squats with ball catches
	Star drill
	Standing on foam with weight shifts and weighted ball in hands
	Romanian dead lifts with weight

IV	Continue selected and numerous drills and activities from phase III
	Plyometrics
	  Side to side:
	    On floor, over tape
	    On floor, four corners
	    Onto one box
	    Onto two boxes
	  Scissor jumps on floor
	  Scissor jumps onto box
	  Skip jumps
	  Bounding drills
	Perturbation training
	Line-to-line lunges
	Running backward
	Running forward
	Lateral slides
	Carioca
	Running start and stop
	Running and cutting (gradual program, cutting 30° to advanced 90°)
	Progress to sport-specific drills

PROM passive range of motion, *EMS* electrical muscle stimulation

Fig. 23.6 Mini-squats performed from 0° to 40° knee flexion on a force platform, allowing the patient to learn to distribute their weight evenly during the exercise

Fig. 23.7 Forward and backward cone walking. The patient is instructed to go through the cones three times each way. The first cycle is performed at normal walking speed. The second is at a faster speed, and the third is at a slower speed to emphasize knee and hip flexion

Fig. 23.8 Lateral cone walking done in the 3-repetition sequence used in the forward and backward cone walking drill

Fig. 23.9 Neuromuscular stimulation applied to the quadriceps to facilitate a muscular contraction

Lateral lunges are initially done on a stable floor surface without resistance. The therapist teaches the patient to land from the lunge with a flexed knee to enhance dynamic stability through co-contracture of the hamstrings and quadriceps (Fig. 23.10). Escamilla et al. [72] and Wilk et al. [52] reported that landing in 30°–40° of knee flexion is the optimal position for hamstring-quadriceps co-contraction. In regard to improving hip strength, the patient may ambulate with a rubber band around the hip (Fig. 23.11). Stability and balance may be increased by performing squats on a Biodex Stability System (Fig. 23.2).

A compression sleeve (Bauerfeind USA, Atlanta, Georgia) is worn when the patient performs daily activities to improve the patient's joint awareness (Fig. 23.2b). Birmingham et al. [73] reported that wearing an elastic sleeve improved proprioception by 25%.

23.10.2 Phase II: Dynamic Stability Phase Drills

In phase II, the dynamic stability phase, drills are slowly increased in degree of difficulty and complexity, transitioning to more combined movement patterns. The exercises are progressed from phase I and require the patient to have mastered specific techniques. For instance, the patient needs to demonstrate the ability to stabilize the knee with a single-leg stance at 30° of knee flexion.

In this phase, the lateral lunge exercise is progressed. The lateral lunge is performed with a resistance cord first in a straight plane (Fig. 23.12), then in a diagonal plane (Fig. 23.13), and finally with rotation (Fig. 23.14). This drill may be progressed to landing on a unilateral surface such as foam (Fig. 23.15) or an air mattress (Fig. 23.16). The goal is to land with the knee

Fig. 23.10 The desired flexed knee landing position during the cone walking drills. The flexed knee position is ideal for co-contraction of the hamstrings and quadriceps musculature

Fig. 23.11 Ambulation performed with a Theraband around the hips. The Theraband is used to create a greater contraction of the hip musculature and emphasize stability of the hip muscles to prepare for sport activities

Fig. 23.12 Lateral lunge performed in a straight plane with the resistance of a SportCord. The goal of this drill is to have the patient land unilaterally and pause in single-leg stance to promote balance and stability

Fig. 23.14 SportCord lateral lunges performed with rotation

Fig. 23.13 SportCord lateral lunges performed in the diagonal plane

Fig. 23.15 SportCord lateral lunges performed onto an unstable surface, such as a piece of foam or rocker board. The foam or board is used to create an unstable surface for landing so that the patient's proprioception is improved

Fig. 23.16 SportCord lateral lunges performed onto an air mattress to create an unstable landing surface

flexed to 25°–30° and the hip flexed to approximately 30°–45° because this promotes a stable joint from co-contraction of the quadriceps and hamstrings [52].

Other drills include front step-downs (Fig. 23.17) and lateral step-ups. The front step-down may be performed with half-circle foam under the patient's foot or with an additional ball catch (Fig. 23.18) to diminish the patient's conscious awareness of their knee joint. One study [74] reported that performance on the front step-down correlated to the patient's functional level and degree of satisfaction.

Squats on an unstable surface are excellent to perform in this phase, such as on a BOSU ball (Fitness Quest, Ashland, Ohio, Fig. 23.19) or a Biodex Stability System. Single-leg balance on foam, a BOSU ball, or unstable platform is used to activate the hip abductors and control femoral internal rotation and adduction. Drills such as the front step-down are excellent to train the hip musculature. In addition, during this phase, hip rotation strengthening exercises are strongly

Fig. 23.17 The front step-down performed on a box. The ability to perform this exercise correlates with the patient's functional level

Fig. 23.18 The front step-down performed with a foam pad underneath the patient's foot to challenge the patient's proprioceptive system. The patient can be additionally challenged by adding a ball toss to the drill to decrease the patient's conscious awareness. A rubber band is placed around thigh to activate the hip abductors

Fig. 23.19 Mini-squats performed on a BOSU ball. The patient is instructed to perform a mini-squat and hold the position while they catch a ball. The patient must hold this position until the ball is thrown back to the clinician

Fig. 23.20 Mini-squats performed on a tiltboard with perturbations. The patient is instructed to keep the board level as the clinician creates a disturbance either by tapping the board with his foot or by tapping the patient at the hips

emphasized through a variety of exercise drills along with foot and ankle exercise drills.

Endurance exercises are gradually implemented. Numerous authors [75–77] have shown that once a joint is fatigued, proprioception is significantly decreased (in some cases, up to 75%). Wojtys et al. [77] demonstrated a significantly slower response time in the quadriceps, hamstrings, and gastrocnemius post a fatiguing protocol.

23.10.3 Phase III: Neuromuscular Control Drills

The third phase of the rehabilitation program introduces randomly designed drills which are performed in combined functional movement planes. In addition, most of these drills combine knee stabilization drills with sport-specific activities and other techniques to create higher levels of functional demands.

Perturbation drills are begun on a rocker board, progressing from bilateral squats (Fig. 23.20) to single-leg holds at 30° flexion, to single-leg squats from 0° to 45° with holds, to single-leg holds at 30° flexion with a ball throw and catch (Fig. 23.21). The clinician either taps the rocker board or the patient to create a postural disturbance throughout these movement patterns. The patient is asked to maintain the platform in a horizontal position and to correct the board position after the perturbation force. These drills may also be performed on a Biodex Stability System. Step lunges onto a tremor device (Fig. 23.22) or a tilt board also challenge the neuromuscular system and are used during this phase of rehabilitation.

Plyometrics may be initiated in this phase using a leg press, with both legs working together.

Fig. 23.21 Single-leg balance holds on a tilt board with ball toss and perturbations. The patient is instructed to maintain a single-leg stance while throwing a medicine ball into a toss-back trampoline while perturbations are produced by the clinician

Fig. 23.22 Lunges performed onto a tremor box device. The patient must lunge forward and land in the center of the platform. The patient is instructed to hold the position for a moment before returning to the starting position. This exercise may also incorporate a ball toss to increase the challenge

Fig. 23.23 The Monitored Rehab Systems (CDM Sport, Fort Worth, Texas) leg press or squat machine. The system combines proprioception and neuromuscular training with strength training

Leg press plyometrics are initiated before floor jumping drills because it appears to be easier to control the patient's body position. A preferred drill is the plyometric leg press four corners (Fig. 23.23) because it enhances both proprioception and coordination.

23.10.4 Phase IV: Functional and Skill Phase Drills

The final phase is the skill and the return-to-activity phase. Several neuromuscular training drills are used to prepare the patient to return to sport activities, including plyometric exercises, perturbation drills, technique drills, and sport-specific progression drills. The plyometric exercises are progressed to jumping on the floor and/or over a cone or hurdle to box jumps. The patient begins with one-box jumps (Fig. 23.24), followed by two-box jumps (Fig. 23.25), and finishes with four-box jumps.

A running program is initiated with backward running in order to promote knee flexion and muscle co-activation. Higher EMG activity of the quadriceps and hamstrings has been recorded during backward running compared to forward running [78]. The patient progresses to side shuffles, cariocas, and then forward running. Once the patient demonstrates a normal gait pattern

Fig. 23.24 One-box plyometric jump exercise. The patient jumps from the floor to the box and back down while being given cues to land with “quiet feet.” This can be done front to back or side to side. The patient is instructed to land and not allow the knee to move into a valgus position. The quality of the landing phase of the jumps is more important than the speed or amount of jumps performed

during forward running, running and deceleration drills and running and cutting drills are performed.

After these drills are mastered, the patient begins a sport-specific training program that includes, for example, specific soccer or basketball ball handling and shooting drills. Proper technique and form are critical. If the rehabilitation professional detects any problems with technique, the drill is stopped to both protect the motor skill and allow education of the patient for the desired technique.

Many tests may be performed to determine the ability of patient to progress from one phase to the next in a safe manner, including isokinetic muscle testing, knee arthrometer testing, and functional single-leg hop testing [79, 80]. The specific criteria required to advance through the rehabilitation program phases are shown in Table 23.3.

Fig. 23.25 Two-box plyometric jump exercise. The patient begins between two boxes on the floor. The patient jumps from the floor laterally to one box, back down to the floor, and then the opposite direction to the second box. The patient is instructed to land with “quiet feet” and to avoid a lower-limb valgus position.

Conclusions

Following ACL injury, there exists a significant compromise of the static and dynamic stabilization capabilities of the knee joint. Noteworthy changes may occur in the activation patterns of the muscles around the knee joint. The rehabilitation program for ACL injuries treated either conservatively or operatively must restore normal knee motion, joint stability, and muscular strength. The program is balanced and exercises progressed in a manner that allows regeneration of the ACL graft. The neuromuscular system is a vital component that the rehabilitation program must consider in all patients with ACL injuries. Therefore, the program must incorporate neuromuscular training as soon as possible after the injury or surgery to ensure an eventual full and satisfactory return to activities.

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24

Role of Isokinetic Testing and Training After ACL Injury and Reconstruction

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Abstract

This chapter focuses on the role of isokinetics with regard to testing and training after ACL injury and reconstruction. This includes the use of isokinetics for screening, evaluation, treatment, rehabilitation, and criteria for discharge to return to sports. Specific considerations for testing after ACL reconstruction are detailed. Testing and training protocols are provided.

24.1 Introduction

Anterior cruciate ligament (ACL) injuries are common; approximately 350,000 ACL reconstructions (ACL-R) are performed annually in the USA [1]. ACL injuries have both short-term [2–4] and long-term [2, 5–10] implications regarding the health of the knee and quality of life [11–14]. In our view, isokinetics can play a significant role in the screening, evaluation, treatment, rehabilitation, and criteria for discharge to return to play (RTP) for the athlete with an ACL injury. The purpose of this chapter is to focus on the role of isokinetics with regard to testing and training after ACL injuries and reconstructions.

24.2 Historical Perspective of Therapeutic Exercise Interventions

Historically, the following trends were observed during the evolution of testing and rehabilitation for ACL injuries:

- 1960s–1970s: Integrated approach using open kinetic chain (OKC) (isolated joint exercises), closed kinetic chain (CKC) (multi-joint exercises), and functional rehabilitation interventions.
- 1980s: OKC isokinetic testing and rehabilitation.
- 1990s: Focus almost exclusively on CKC exercises because they were considered more functional.
- 2000s: “Functional rehabilitation” that has persisted because of the (supposed) specificity

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of activities. Multiple joint exercises with a variety of movement patterns were used to simulate various activities.

- 2010s: Trend to revert back to integrated OKC, CKC, and functional rehabilitation approach recommended.

One of major reasons we hope the trend will recycle is because for the last 20–25 years, the major emphasis in rehabilitation of ACL injury and reconstruction has been on CKC and functional exercises. Changes have occurred in rehabilitation programs that are as important as ACL reconstruction in allowing patients to return to function or sports. Published recommended time frames for RTP ranged from within 3 months [15] to 2 years [16]. However, Ardern et al. [17] in a meta-analysis reported only approximately 55% of patients returned to their premorbid level of activity. The primary criteria that influenced the ability to return to the same level of sports were younger age, male gender, elite sports athlete, and quadriceps strength. These findings may be interpreted to indicate that the emphasis placed on CKC exercises and functional rehabilitation failed in 45% of ACL patients. This study illustrates that quadriceps strength is one modifiable risk factor that is directly under the control of the clinical rehabilitation specialists that has a significant impact on RTP.

Isokinetics were developed in the 1960s [18, 19], and usage peaked in the 1980s because of the increasing body of evidence demonstrating its effectiveness in assessment and rehabilitation of patients with knee injuries. The first book dedicated to isokinetics was published in the early 1980s [20]; this text provided information on testing protocols and rehabilitation interventions using unique concepts such as velocity-spectrum rehabilitation protocols (VSRP). Despite extensive literature supporting its clinical applications (approximately 2000 articles in the 1990s), and the development of the journal *Isokinetics and Exercise Science*, many practicing clinicians discontinued using isokinetics. However, a recent PubMed search using the term *isokinetics* yielded 6317 references, with 3087 articles focused on knee testing and rehabilitation.

Although most clinicians believe using only CKC exercises or functional exercises is effective for rehabilitation, the literature does not support this concept. There are numerous rehabilitation programs that focus on resistive exercises, particularly during the later stages of ACL rehabilitation. However, there is significant practice variation, with few level I or II studies that demonstrate the most efficacious therapy program. For instance, recent studies [21, 22] compared the Multicenter Orthopaedic Outcomes Network rehabilitation protocols with the Delaware-Oslo rehabilitation programs for patients with ACL injuries. Many of the interventions described in the Delaware-Oslo program were more effective in producing better outcomes. A recent systematic review by Kruse et al. [23] of 29 level I or II studies reported the following conclusions: "Neuromuscular exercises should not be performed to the exclusion of strengthening and range of motion exercises." This reinforces the concept of working each link in the lower extremity kinematic chain first to establish a good solid foundation. Furthermore, these authors concluded that "Neuromuscular exercises are not likely to be harmful to patients, however, their impact is small, making them unlikely to yield large improvements in outcomes or help patients return to sports faster."

24.3 Overview of Terminology and Assessments

There are various modes of activities and movements that can be used for testing, prevention, and rehabilitation that have been described in the literature including isometrics, isotonics, variable resistance isotonics, plyometrics, and isokinetics. Whereas isotonic exercises use a fixed resistance that can be moved at a variable velocity throughout the range of motion (ROM), isokinetics uses a preset fixed velocity while allowing for accommodating resistance through the ROM. The fixed velocity ranges from 1°/s to approximately 1000°/s. The accommodating resistance exactly matches the active muscle force produced by the patient throughout the ROM, thereby providing the only way to dynamically load a muscle to its maximum capability at every point through the ROM. This is an important concept, because as a joint goes through ROM, both the biomechanical leverage of the joint and the length-tension ratio of the muscle (Blix curve) change. These changes potentially influence the muscle force capabilities throughout the ROM.

24.3.1 Closed Kinetic Chain Exercises

CKC exercises are typically described as exercises in which the distal end of the extremity is in contact with a surface that provides considerable resistance. Based upon the kinematic patterns that are evident during CKC exercises, they are also described as multiple joint exercises. Classic examples include squats, lunges, and leg press motions. Although the benefits of using CKC exercises in rehabilitation have been extensively described, few scientifically based prospective randomized controlled trials have been published that exclusively used CKC exercises after ACL injuries and reconstructions that demonstrated excellent outcomes. The reader is referred to a text [24] that outlines many of these studies and the applications to complement the material presented in this chapter.

24.3.2 Open Kinetic Chain Exercises

An OKC exercise usually refers to exercises in which the terminal end of the extremity is free in space. OKC exercises are also commonly described as isolated joint exercises. A classic example is a knee flexion-to-extension pattern while seated. The majority of isokinetic testing and rehabilitation exercises are known as OKC or isolated joint movements.

24.3.3 Functional Movement Exercises and Assessments

There exists today a trend to use different functional movement analysis studies to assess “functional movements” [25–27]. Most of these systems use gross movement patterns and few are truly actually used in sports activities. For instance, a recent systematic review indicated that although the Functional Movement System (FMS) is reliable, it has poor validity [25]. The originators of the FMS selected an arbitrary set of 6 movement patterns, and other than the squat, none have specific application to functional activities or movement patterns in daily or sports activities. While it is important to evaluate a functional movement pattern, if a deficit exists, it is important to identify the cause of the problem. Muscle performance is usually evaluated with manual muscle testing (MMT), handheld dynamometry (HHD) [28], or isokinetic dynamometry. One of the disadvantages of both MMT and HHD is that the muscle testing is performed using an isometric resistance. Dynamic movements are required in sports activities, and there is minimal correlation of isometric testing to dynamic functional muscle performance or functional activities. Isokinetic testing allows for dynamic muscle performance testing which has been shown to correlate with functional movements [29–34].

If a functional test suggests the presence of weakness, the specific source of the weakness cannot be determined because multiple muscle groups are simultaneously contracting. Therefore, isolated testing of selected muscles in the lower extremity is required [35–37]. A popular term used in the literature is *regional interdependency*, which illustrates the interactions of the entire kinematic chain. Interestingly, the concept of total leg strength (TLS) testing was reported in the literature over 40 years ago by Nicholas et al. [38]. Gleim et al. [39] determined that the total percent deficit in the injured leg was the most informative value. Generally, when a single muscle group is analyzed in a bilateral comparison, the $\leq 10\%$ empirically based guideline is used to identify symmetry. Because the TLS composite score is more sensitive and minimizes the variability that may occur with one muscle group, these authors suggested that even a 5% difference in a bilateral comparison was significant. Other studies by Bolz and Davies [40] have supported the importance of regional interdependency of TLS testing. Testing the proximal muscles is especially important, because they help control the kinematics of the lower extremity in the frontal and transverse planes [35–37].

An example of the importance of performing TLS testing, with emphasis on assessing the role of the proximal muscles, was described by Hewett et al. [41, 42] in regard to women demonstrating greater valgus collapse of the lower extremity primarily in the frontal plane. This is indicative of weaknesses of the hip abductors and hip external rotators, which should be detected with TLS testing. Brent et al. [36] reported postpubertal females had altered hip recruitment strategies for controlling landing, with significantly greater hip moments, higher knee-to-hip moment ratios, decreased gluteus maximus activation, increased rectus femoris activation, and greater hip abduction angles and moments compared with males. The TLS concept appears critical in the female athlete. We recommend performing not only functional performance tests that are specific to the sporting activity but also isokinetic isolated testing of the muscle groups for TLS that make up the kinematic chain.

24.4 Testing and Training with Isokinetics

24.4.1 Advantages and Limitations

Isokinetic testing and rehabilitation use a preselected fixed angular velocity with accommodating resistance. Therefore, velocity-spectrum testing (60°/s, 180°/s, 300°/s, 450°/s) is performed to sample the muscles' abilities at slow, medium, and fast angular velocities. As a result of the accommodating resistance, there is an inherent safety factor because the patient will never meet more resistance than they can handle because the resis-

Table 24.1 Advantages and limitations of isokinetic testing

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 capability 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 postexercise 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 are important for athletic performance • The reciprocal inneration time is the time from contracting one muscle group (agonist) (quadriceps), and then reciprocally contracting the opposite muscle group (antagnoist) (hamstrings). When the patient exercises at faster angular velocities in a reciprocal manner (contracting quads and then immediately the hamstring, etc.), it decreases the reciprocal innervation time • Joint compressive forces decrease with higher angular velocities (fluid film lubrication model) • Bernoulli's principle indicates that the faster a surface (articular cartilage) moves over fluid, (synovial fluid in a joint), the less the compressive forces on the surface • 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 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 • Increased joint compressive forces at slower speeds • May cause increased anterior tibial translation with testing or rehabilitation if using full range of motion

tive torque produced is based on the effort applied by the patient. Some additional advantages, as well as limitations, of isokinetic testing and exercises are shown in Table 24.1 [20, 43, 44].

24.4.2 Correlation with Closed Kinetic Chain Tests and Functional Performance

A valid reason to perform OKC isokinetic testing is the relationship with CKC tests and functional activities. Several studies [29–34, 45–47] demonstrated positive correlations between OKC isokinetic testing and functional performance as measured with various performance tests. For instance, Wilk et al. [48] reported significant associations between subjective knee scores, isokinetic testing, and functional tests. Patel et al. [46] performed isokinetic testing on 44 normal subjects and 44 patients with ACL-deficient knees. The group with ACL deficiency had significantly weaker isokinetic quadriceps strength than the control group. The difference in strength was related to significant decreases in the peak external quadriceps moment during jogging, jog-stop, and jog-cut activities, as well as stair ascent. Karanikas et al. [45] correlated findings between isokinetic muscle strength and walking and running kinematics. After ACL reconstruction, patients who had significant strength deficits also demonstrated abnormal strategies of locomotion kinematics. Petschnig et al. [47] reported a relationship between isokinetic strength testing and several lower extremity functional tests. Wilk et al. [48] found that isokinetic tests at slower speeds did not correlate with functional tests; however, faster speeds (>180°/s) revealed significant relationships. Admittedly, performing isokinetic testing of an isolated joint movement does not replicate the true angular velocities of many functional activities. However, the angular velocities with functional activities are a summation of angular velocities generated throughout the kinematic chain. Because most functional movements involve faster angular velocities, velocity-spectrum testing with emphasis on results from faster testing velocities is recommended.

24.4.3 Contraindications for Testing

Absolute contraindications for isokinetic testing include acute muscle-tendon unit strains, acute ligament or capsule sprains, soft tissue healing constraints, severe pain, extremely limited ROM, severe effusion, and joint instability. Relative contraindications include subacute muscle-tendon unit strains, subacute ligament or capsule sprains, pain, partially limited ROM, effusion, and joint laxity.

24.4.4 Test Protocols

Consistent testing protocols should be established to enhance reliability of testing. Often, there will be different protocols for athletes based on the demands of their sport or activities. As with any formal dynamic testing procedure, specific steps should be established for consistency. Examples include:

1. Educate the patient regarding specific requirements for the test.
2. Test the noninvolved extremity first to establish a baseline and show the patient what is expected when the involved side will be tested.
3. Perform gradient submaximal to maximal warmups (25%, 50%, 75%, 100% of maximum effort) at each speed to be tested.
4. Use consistent verbal commands for the patient to follow such as “push and pull as hard and fast as possible.”
5. Use standard test protocols for each joint/pattern.
6. Have the equipment properly calibrated.
7. Properly position and stabilize the patient on the testing equipment.

We recommend using a velocity-spectrum testing protocol (60°–180°–300°–450°/s) to sample the muscle’s capabilities at different speeds to assess its performance capabilities simulating various functional activities. We recommend five repetitions at each velocity, with a 30–60 s rest between each velocity of testing. Often, an endurance testing protocol may be used that involves 30–40 repetitions at 300°/s; assess for work decrement from the first 20% to the last 20% of repetitions. Various pathologies may manifest more appreciably at one speed. There are a variety of testing protocols for strength, power, and endurance tests described elsewhere [20, 43].

Power, particularly of the quadriceps muscles, is one of the most important parameters of muscle performance because it is reflective of functional performance [49–55]. It has also been demonstrated [49] that the rate of force development (RFD) is a key indicator of muscle deficits after ACL-R. Consequently, MMT and HHD cannot capture dynamic muscle performance which is critical to assess when making decisions regarding RTP. Sports activities involve high degrees of RFD to help stabilize the knee during cutting, twisting, and reactive movements. Dynamic muscle performance testing, with the ability to measure not only peak torque, but other critical parameters of muscle activation, is necessary to safely make clinical decisions regarding the effectiveness of muscle performance [49, 56, 57].

24.4.5 Data and Analysis

Advantages of isokinetic testing include the extensive objective parameters that can be used to evaluate and analyze an athlete's muscle performance [20, 43, 52, 58–63] (Table 24.2). The most commonly used data methods to assess muscle performance are illustrated in Figs. 24.1 and 24.2 [20, 43, 61]. Eitzen et al. [64] provided isokinetic test data relevant to patients with ACL injuries in the evaluation of concentric quadriceps muscle strength torque values at peak torque

Table 24.2 Isokinetic test measures

Measure	Definition
Peak torque	The maximal torque value recorded during a set of repetitions
Average peak torque	The average of the maximal peak torques for each repetition within a set
Angle-specific torque	The torque at a specific angle in the ROM
Time rate of torque development (TRTD) to peak torque	The elapsed time from torque production onset to peak torque
Time rate of torque development to predetermined time	Torque produced at predetermined time; can be considered qualitatively as slope of torque curve or quantified by the peak torque at the predetermined time (typically 0.2 s)
Time rate of torque development to specific ROM point	Time to reach a specific point in the ROM
Torque acceleration energy (TAE)	Total work performed in the first 0.125 s
Reciprocal innervation time (RIT)	The time interval from cessation of agonistic torque production to the initiation of antagonistic torque production
Torque decay rate	Downslope of torque curve; in general, the downslope should be qualitatively straight or convex; concave suggests difficulty producing torque at the end ROM
Total work	The area under the torque-angular position curve
Work fatigue	The amount of work produced in the first third of a set divided by the amount of work produced in the last third of a set; important that at least 15–40 repetitions be completed for this measure
Average power	Total work divided by the time to perform the work. This is a measure of the "explosiveness" of a muscle
Coefficient of variation (CV)	The standard deviation of torque values through the ROM for each repetition in a set divided by the average torque value across all repetitions of the set; used to indicate consistency of effort across the repetitions in the set. An empirically based guideline is to use a 10% CV
Qualitative analysis	This is the clinician's interpretation of the torque curve which has been shown to reflect selected deficits

ROM range of motion

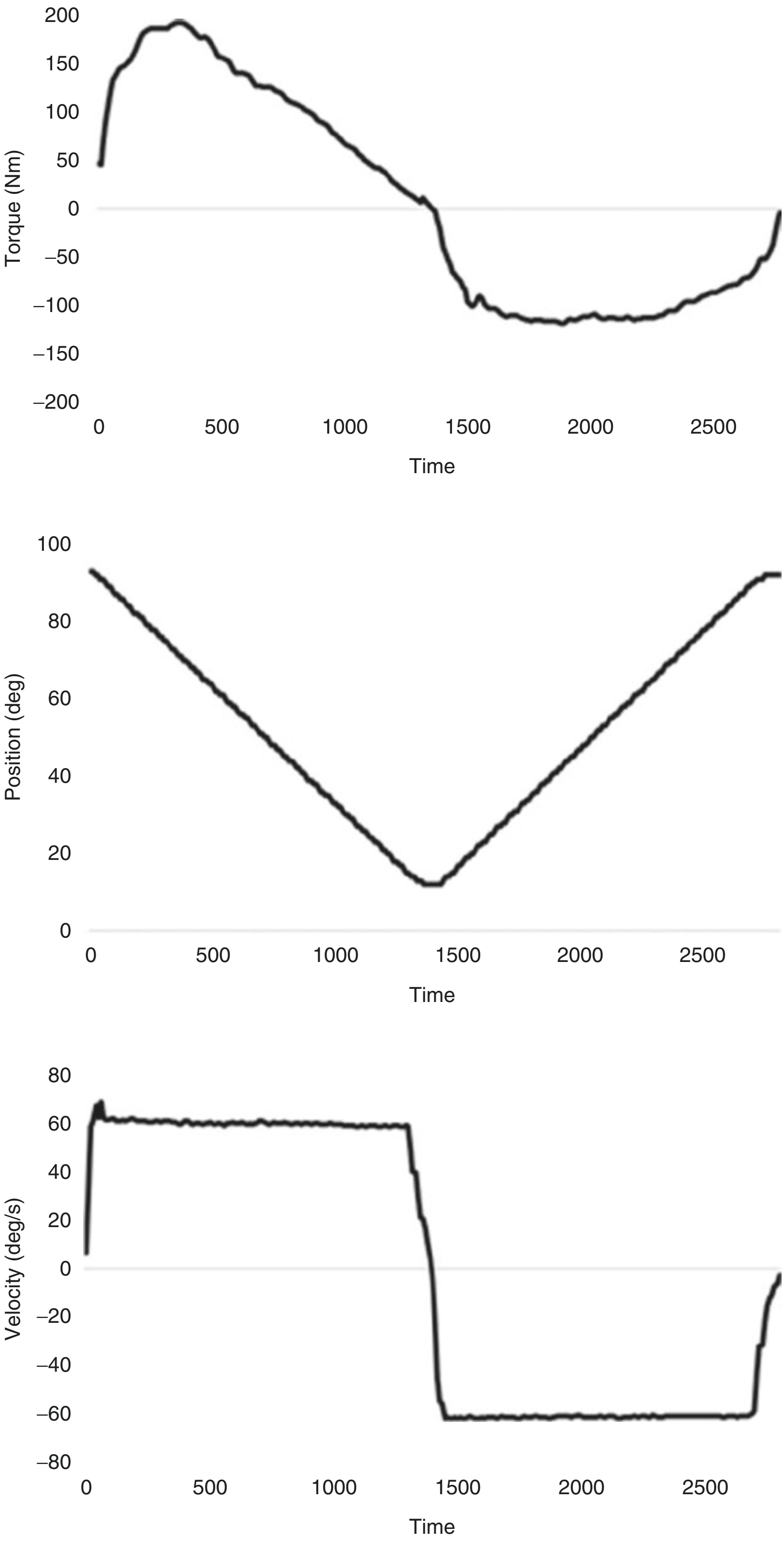

Fig. 24.1 Typical torque, angular position, and velocity curves for a knee extension-flexion isokinetic test at 60°/s. The test began with the knee in 90° flexion. Extension torque and velocity are positive

and specific joint angles. Peak torque was consistently measured at 60° of knee flexion, whereas the largest mean deficits were measured at either 30° or 70°. This study underlines the importance of including torque at specific knee joint angles from isokinetic assessments, and not just peak torques, to identify the most severe quadriceps muscle strength deficits.

There are common techniques of analysis and interpretation of isokinetic data. A general comparison to begin data interpretation is bilateral comparison, or the analysis of torque values of one extremity relative to the other extremity [65]. The most commonly used parameter is ≤10% difference to indicate bilateral symmetry. However, after ACL injury and ACL-R, the contralateral leg usually has a detraining effect and is not in its "normal" status to use as a baseline for return to normal. If a patient has pre-participation data, or preseason screening data, then they should ideally be returned back to the preinjury status. Otherwise, allometric scaling of the data needs to be determined. Ford et al. [66] demonstrated that asymmetrical loading of the limbs after ACL injury was a potential ACL injury risk factor. Consequently, identification of asymmetry is an important component for safe reintegration of patients back to sports activities. Myer et al. [67] also indicated deficits in muscle strength, power, coordination, or activation patterns potentially increase injury risk due to increased joint loads as neuromuscular deficits.

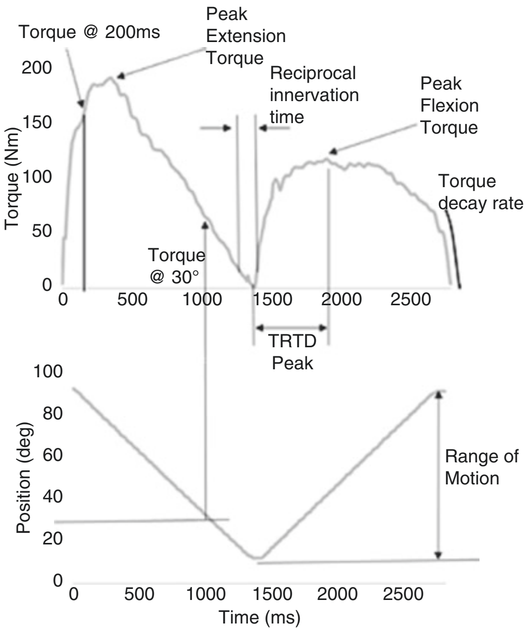

Fig. 24.2 Common measures used to reflect isokinetic muscle performance. Torque and position data are from knee extension-flexion test at 60°/s. Flexion torque has been made positive

Unilateral ratios, or comparison of agonist and antagonist muscle torques, are particularly important to assess with velocity-spectrum testing because the ratios change with different angular velocities in most muscle groups [68, 69] (Table 24.3). Muscles provide synergistic dynamic stability to the knee joint, and we believe it is important to assess the unilateral ratio of the quadriceps and hamstrings. Most of the literature indicates that patients have quadriceps deficits for prolonged periods of time after ACL-R, even with appropriate rehabilitation [59]. Furthermore, because the ACL-deficient knee has increased anterior tibial translation, the hamstrings act as dynamic stabilizers [70, 71]. Consequently, we bias these muscles and try to create a hamstring-dominant knee to provide synergistic co-contraction and stability. As an operational definition, we try to bias the unilateral hamstring/quadriceps ratio by strengthening the hamstrings approximately 10% higher than the normal unilateral ratio for the respective velocity of testing. Other studies have shown the importance of assessing unilateral ratios [67, 72, 73].

Allometric scaling is one of the most important considerations for data analysis in order

Table 24.3 Isokinetic unilateral ratios and allometric data to body weight

		Allometric scaling (% body weight)	
Outcome measurement (°/s)	Hamstrings/quadriceps unilateral ratio (%)	Males	Females
60	~60–70	90–100	80–90
180	~70–80	70–80	60–70
300	~85–95	45–55	30–40

to individualize the test results to the patient, which should be done relative to the patient's body weight. As previously mentioned after an injury and/or surgery, there is usually a detraining effect. Consequently, the muscular force characteristics of the uninvolved side decrease and are not representative of the "normal" performance characteristics of the muscle. Similar to the bilateral comparison, allometric scaling is relative to the velocity of the testing as well.

A fourth technique is TLS assessment, or the composite score of torque values for individual components of the leg. Finally, there is comparison to normative data. Although there may be some controversy over the use of normative data, if used appropriately relative to a specific sport and/or position within a sport, it can provide useful guidelines for testing and rehabilitation.

Research has demonstrated the relationship between the shape of the isokinetic torque curve and joint function. Consequently, performing a qualitative analysis of the torque curve may be valuable in the data analysis. Bryant et al. [59] demonstrated that specific characteristics of the isokinetic torque curve of the knee extensors (extensor torque smoothness) may provide valuable clinical information regarding joint function. The morphology of knee extension torque-time curves demonstrated that after ACL reconstruction, the involved knee had significant deficits. Eitzen et al. [63] evaluated isokinetic strength profiles in ACL-deficient potential copers and noncopers. Results demonstrated that the peak torque did not identify the largest quadriceps muscle strength deficits; rather, it was established at knee flexion angles <40°. The results demonstrated significant differences in angle-specific torque values between the copers and noncopers. This is the functional angular position with many cutting, twisting, and pivoting activities where ACL injuries occur. This further illustrates the need to perform data analysis of angle-specific torques and not just peak torques that typically occur in the mid-ROM where the optimum biomechanical leverage for a joint and length-tension ratio of the muscles creates the maximum force production.

24.5 Using isokinetics within the exercise progression continuum

Rehabilitation programs are designed along a progression continuum beginning with the safest and gradually progressing to more difficult resistive exercises. This concept was published over 30 years ago [20, 43] and still serves as a guideline for designing therapy protocols. Each link in the kinematic chain is worked first to establish a good foundation, and then advanced exercises are added with the volume dosage continually monitored and progressed. We note that if a clinician tests each link in the kinematic chain and all are "within normal limits," there appears to be no need to work each link to establish a solid foundation. One of the concerns with this approach is that clinicians rarely evaluate the muscle performance of each link in the kinematic chain for many reasons: time constraints in a busy clinic, lack of equipment, or insufficient knowledge of the importance of the regional interdependency and TLS concepts.

The majority of muscle groups have approximately 50% slow-twitch (ST) and 50% fast-twitch (FT) muscle fibers. Nakamura et al. [74] performed histochemical studies on 112 patients (52 athletes) to determine whether there was a different susceptibility of muscle fiber types in the vastus lateralis (VL) in knee joint disorders. There were ACL injuries in 51 patients, ACL and meniscus (ACL + M) injuries in 29, meniscus tears in 25, and collateral ligament tears in 7. Atrophy of type-1 fibers was found in ACL and ACL + M injuries. Type-2 fibers were atrophied in all groups. The study concluded that atrophy of type-1 fibers may relate specifically to ACL insufficiency.

Since power is one of the most important characteristics of muscular performance, the issue of finding and developing the most effective rehabilitation and training methods to produce power is valid. There are only four ways to recruit FT fibers: (1) the all-or-none recruitment phenomenon (maximum intensity effort, which is not practical for patients due to soft tissue healing, pain, apprehension, and inability to activate the muscles adequately), (2) electrical stimulation, (3) blood flow restriction training, and (4) fast movement patterns with maximum intensity, indicating the need to perform fast velocity isokinetic exercises in addition to functional specificity training. If isokinetic equipment is available and no contraindications are present, we recommend using isokinetics because of the accommodating resistance. Hewett et al. [42] reported that it was possible to induce a neuromuscular spurt and improve neuromuscular deficits in females with training. Being able to supplement functional training with isokinetic training may be even more effective because of improving the foundational strength of each link in the kinematic chain/TLS.

Numerous studies [34, 75–88] have demonstrated the efficacy of OKC and/or isokinetic exercise in improving muscle performance. By performing isolated dynamic isokinetic exercises

Table 24.4 Isokinetic rehabilitation exercises

Exercise	Description
Multiple angle isometrics: submaximal intensity	Specific angles are dictated by the patient's status. Initially, angles between 90° and 30° are used to prevent additional stresses to the ACL due to the anterior translation and external rotation (screw-home mechanism). If the patient has patellofemoral problems, then the angles are dictated by symptoms. The intensity is dictated by time with soft tissue healing constraints, pain, effusion, and the patient's ability to activate the muscles. This is generally between 30% and 60% of MVC during the early phases of rehabilitation
Multiple angle isometrics: maximal intensity	Same concepts as above, but increase intensity >60% MVC to begin recruiting FT (subtypes FTA, FTX, FTB) muscle fibers. The same guidelines are used to protect soft tissue healing, avoiding areas of chondral damage, respecting symptoms, etc.
Short-arc (ROM) isokinetics: submaximal intensity	Short-arc exercises are used for dynamic muscle strengthening when full ROM is contraindicated and there are no contraindications to begin dynamic exercises. Begin in 90°–30° range. Use medium angular velocities to minimize the amount of free limb acceleration (60°–180°/s). Avoid angular velocities <60°/s because of increased joint compressive forces, abnormally slow motor patterns, and pain. Angular velocities in multiples of 30°/s are used because of the physiologic overflow and strengthening effects. Similar principles of the intensity of the exercises apply to the dynamic short-arc exercises as described above
Short-arc (ROM) isokinetics: maximal intensity	Similar principles for the application of intensity and volume dosage would be applied as described above using maximal effort
Full-arc (ROM) isokinetics: submaximal intensity	When there are no contraindications (such as soft tissue healing constraints with an ACL-R), full-arc dynamic isokinetic exercises can be performed. Increases in isokinetic strength are primarily velocity-specific (110); incremental velocities of 30°/s may be used to achieve physiologic overflow at slower speeds
Full-arc (ROM) isokinetics: maximal intensity	Similar principles of the intensity of the exercises and the overflow principles apply to the dynamic full-arc exercises. Use a VSRP; perform 10 repetitions at each speed; increase from 180 to 300°/s and then back down from 300 to180°/s
Neuromuscular dynamic stability exercises	These exercises may be used to mimic the activities the patient will return to and are implemented in a progressive, controlled manner in the clinical setting to control the volume dosage loading concept
Plyometrics	Plyometrics develop explosive power that is required for most sports activities. Begin with basic jumping and hopping drills; progress to box-jumping drills and finally to drills that replicate sport-specific movement patterns
Functional specificity exercises	It is difficult to actually replicate many of the multi-planar high-velocity, reactive drills in a clinical setting. This phase of the rehabilitation program needs to have a gradual return to sports practice situations in a controlled manner. Progress intensity, reactivity, and specificity to performing the movement patterns required for full return to sport

Table 24.4 (continued)

Exercise	Description
Rest intervals	When a patient performs an isokinetic VSRP exercise bout, the rest interval between each set of 10 repetitions may be as long as 90 s to replace the triphosphate and creatine phosphate in 20 s after an acute bout of muscular work. Seventy-five percent and 87% of intramuscular stores are replenished in 40 s and 60 s, respectively. Knowledge of the phosphagen replenishment schedule allows the clinician to make scientifically based decisions on the amount of rest needed or desired after periods of muscular work. If the patient completes a total VSRP, a rest period of 3 min has been shown to be an effective rest interval. Another critical factor in determining optimal rest intervals with isokinetic exercise is specificity. Applying activity or sport-specific muscular work-rest cycles can be an important consideration during rehabilitation

FT fast twitch, *MVC* maximum volitional contraction, *VSRP* velocity-spectrum rehabilitation protocol

Table 24.5 Clinical measures for isokinetic test deficits

Measure	Clinical measures for deficits
Peak torque	Perform full ROM isokinetic exercises using a VSRP. Short-arc isokinetic exercises in the ROM are used to improve muscle activation at mid-ROM, which is typically about where peak torque occurs
Average peak torque	Similar to above approach, except emphasize short-term isokinetic endurance training to increase torque at all repetitions
Angle-specific torque	Perform short-arc isokinetic exercises, focused at the angle where the deficits were identified during the test
Time rate of torque development to peak torque	Perform short-arc isokinetic exercises at the beginning of the ROM. Primary emphasis on short-arc VSRP (60°–90°–120°–150°–180°–180°–150°–120°–90°–60°/s). As the speed is increased, if the patient has difficulty “catching the machine” (accelerating to the predetermined speed to create true isokinetic loading), they should be trained at that speed so they can activate the muscle quickly and accelerate the extremity. Once they can “catch the machine,” increase the speed to keep challenging the muscles to contract and generate power as quickly as possible
Time rate of torque development to predetermined time	Use similar concept as above, but use time as the motivator
Time rate of torque development to specific range of motion point	Use similar concept as above, but focus on generating torque within a certain ROM
Torque acceleration energy	Total work performed in the first 0.125 s. This is similar to the techniques used for the TRTD to predetermined time
Reciprocal innervation time (RIT)	Patient begins by performing an isometric muscle contraction of the agonist muscle, and then the dynamometer is quickly switched to a dynamic speed so they have to contract the antagonistic muscle. The initial speeds are slow so the patient can “catch the machine” and then the speeds are progressively increased. Then, the patient begins by performing short-arc isokinetic exercises with the agonist muscle and then as quickly as possible contracts the antagonistic muscle to decrease the RIT. The velocities can be slowly and progressively increased to make the muscle activations react more quickly. The ROM can also be gradually increased toward full ROM to make the patient activate the muscles as quickly as possible
Torque decay rate	Initial focus is on performing short-arc isokinetic exercises at the terminal end of the ROM. This is often difficult for the patient (depending on the joint and position). The joint frequently loses its biomechanical leverage at the end of the ROM because the muscle fibers are shortened, thereby putting them at a disadvantage to generate force, and frequently the movement is against gravity. Begin with slower velocities in the short arc of motion, and gradually increase the velocity so the patient can “catch the machine.” Use similar guidelines with ROM. Use short ROM initially, and then gradually increase until the patient can maintain the forces throughout the entire ROM, particularly at the ends of the ROM

(continued)

Table 24.5 (continued)

Measure	Clinical measures for deficits
Total work	Because total work is based on the patient producing forces throughout the entire ROM, full-arc exercises are emphasized at the speed where the patient can "catch the machine." However, to increase the work throughout the entire ROM, short-arc isokinetic exercises are performed in the beginning 1/3 of the ROM, mid 1/3 ROM, and end 1/3 ROM. The patient focuses on generating forces with the joint in different biomechanical leverage positions to optimize the forces within this ROM. By working the muscle-tendon unit at different lengths, muscles are strengthened in both lengthened and shortened positions
Work fatigue	In order to facilitate endurance, perform short-duration endurance bouts of isokinetic exercises through the full ROM with appropriate work/rest recovery ratios. Then, decrease work/rest ratios to enhance muscle recoverability. The number of repetitions can also be increased. Use of a VSRP model (100 reps) with isokinetic exercises emphasizes power endurance
Average power	Similar approach described for total work. The major difference is to emphasize the optimum power-generating capability of the patient and train at that speed. The patient's torque plateau represents their optimum power production velocity. The focus of the patient's isokinetic training program would be at that velocity (plateau) using a modified VSRP (10 reps × 10 sets at that speed)
Coefficient of variation (CV)	Perform patient education regarding consistent forces with repetitions that should decrease in a regular pattern with fatigue

RIT reciprocal innervation time, *ROM* range of motion, *TRTD* time rate of torque development, *VSRP* velocity-spectrum rehabilitation protocol

using a TLS approach of the lower extremity (Table 24.4), a foundation of strength is established with all muscle groups [20, 43, 44, 89–92]. After the foundational strength has been recovered, the patient is progressed to more activity or sport-specific exercises. Table 24.5 illustrates how specific testing deficits can be addressed with the use of this continuum and the application of isokinetic exercises.

24.6 Application of Isokinetics After ACL Injuries and Reconstructions

24.6.1 Advantages of Testing

One recurrent problem after ACL injuries and reconstructions is residual quadriceps weakness [45, 53, 93–101]. For instance, Eitzen et al. [102] performed isokinetic testing before ACL reconstruction and reported that if a patient had a 20% quadriceps deficit, then a residual deficit would remain for up to 2 years postoperatively. This emphasizes the importance of pre-rehabilitation for patients with ACL injuries and the use of isokinetic testing to identify deficits that exist with dynamic muscle performance [78, 103, 104]. In addition, several studies [17, 22, 53, 93, 99, 101] have reported that when patients RTS, they had significant quadriceps deficits, which were probably also clinically significant producing residual power deficits.

Davies [76] compared 300 patients using CKC isokinetic testing with a Lido Linea and OKC isokinetic testing using a Cybex system. Subjects were tested at slow, medium, and fast speeds, respectively. The results demonstrated that more significant deficits existed in athletes after OKC isolated joint muscle testing compared with CKC multiple joint muscle testing. Feiring and Ellenbecker [105] tested 23 athletes 15 weeks after ACL reconstruction. They also demonstrated more significant deficits with OKC testing compared with CKC isokinetic testing on bilateral comparisons. Ernst et al. [106] compared vertical jump testing with isokinetic joint testing in patients with ACL injuries. The single-leg vertical jump of each extremity was symmetrical; however, all patients had significant quadriceps deficits on isokinetic testing. In these cases, the proximal and distal muscles compensated for the weak-link quadriceps muscles. When isolated isokinetic testing was performed, the quadriceps deficit was exposed within the kinetic chain.

Several investigations have demonstrated that poor quadriceps isokinetic performance after ACL-R is a risk factor for the development of osteoarthritis (OA) [7, 98, 107]. One study found that patients who had low self-reported knee function and significant isokinetic quadriceps weakness during the 2-year and the 10–15-year follow-up periods had significantly higher odds for symptomatic, radiographically detected knee OA [98]. In addition to quadriceps weakness, low quadriceps-to-hamstring strength deficits have also been reported as an OA risk factor after ACL-R [7]. The clinical application is that conducting an isokinetic test after ACL-R can be used to identify a modifiable risk factor for OA.

Another advantage of performing OKC isokinetic testing is that it provides for excellent clinical control of the speed of movement, the ROM, translational forces (based on the placement of the shin pad), varus and valgus forces, and rotational forces. When performing CKC testing, most control is lost by the clinician and the patient is almost exclusively responsible for the control of the testing motion. For example, when a hop test is used to measure lower extremity power, there are numerous increased stresses to the entire lower extremity kinetic chain, such as valgus forces and rotational forces, particularly during the eccentric deceleration landing phase.

Many studies have demonstrated the benefit of using isokinetically derived outcome measures, in addition to functional performance testing, to evaluate patient progress at various time points after injury [102] and ACL-R [53, 71, 94, 96, 97, 100]. Remarkably, Karanikas et al. [45] demonstrated motor task and muscle strength recovery followed different time frames, because decreases in muscle strength did not impact walking and submaximal running until the strength deficits reached a certain threshold. This clearly suggests the need for both isokinetic and functional movement testing such as walking and submaximal running. Following a systematic review of 90 studies, van Melick et al. [108] developed the most recent practice guidelines for ACL rehabilitation that include isokinetic strength testing in addition to functional performance testing.

24.6.2 Specific Considerations for Testing After ACL Reconstruction

Specific recommendations to consider when testing a patient after an ACL reconstruction include understanding the details of the type of surgery (such as type of graft and fixation) and the graft status before testing (using knee arthrometer, Lachman, and pivot-shift tests). A pre-determined time frame and specific protocol to use at each criterion-based testing time are based on soft tissue healing constraints. Use a proximally placed pad or a dual shin pad to prevent anterior tibial translation [44] (Figs. 24.3 and 24.4), and avoid 30°–0° of knee extension to minimize anterior translation

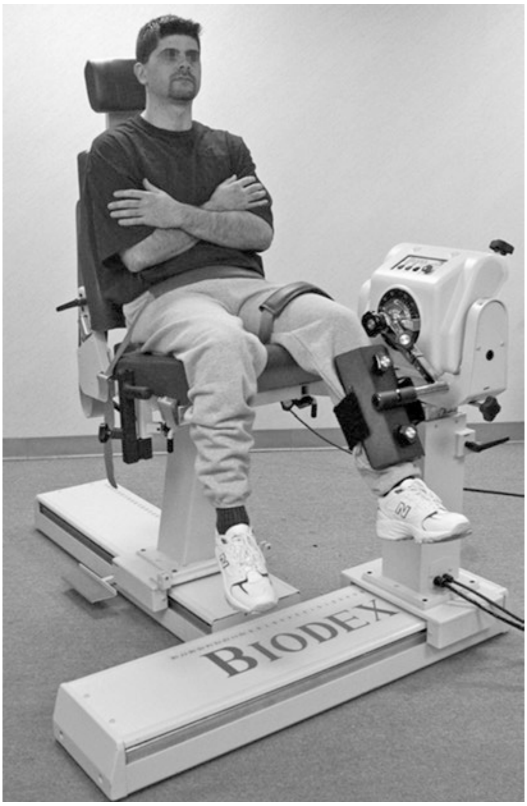

Fig. 24.3 Isokinetic testing with anti-shear pad

Fig. 24.4 Anti-shear pad

(and the obligatory screw-home mechanism). In addition, use faster velocities earlier in the testing and then decrease the speeds for the velocity-spectrum testing as the patient progresses through the rehabilitation session and/or program. This is a variable concept because patients may have difficulty "catching the machine" (moving the limb fast enough to accelerate to the preselected dynamic velocity to create true isokinetic loading through the ROM). In these cases, the speed should be adjusted in order for the test to be valid. Checking the coefficient of variation (CV) and the ROM after windowing the data can be helpful in testing and designing the rehabilitation program.

A frequently cited contraindication for OKC isokinetic testing of ACL-R is potential graft disruption [109–111]. This is an example of good science being applied to an improperly performed isokinetic test. Obviously, soft tissue constraints must govern all testing, whether it be isokinetic or functional. A series of studies [112–116] implanted a dynamic variable reluctance transducer into the ACL and measured its strain in vivo. Recorded ACL strains were 3.5% for OKC knee flexion to extension (100°–0°) in an unloaded condition, 3.6% for CKC squats from extension to flexion (0°–100°), and 4.9% for CKC squats using a sport cord from extension to flexion (0°–100°). These investigators speculated that "it might not be valid to designate OKC or CKC activities as 'safe' or 'unsafe' with respect to rehabilitation of the injured ACL or healing graft." Furthermore, by limiting ROM with a proximally placed pad or a dual shin pad [44], and respecting the temporal components of soft tissue healing, there should never be an injury to the ACL graft with proper testing and rehabilitation applications by an informed clinician.

24.6.3 Potential Problems with Isokinetic Training After ACL Reconstruction

A question frequently arises regarding the use of OKC and isokinetics and development of knee pain during rehabilitation after ACL reconstructions. A few studies have addressed this problem and found similar results [84, 86]. Morrissey et al. [82, 83] placed patients into either an OKC or CKC rehabilitation program. They concluded that OKC and CKC leg extensor training in the early period after ACL-R did not differ in regard to anterior knee pain. Hooper et al. [79] demonstrated no clinically meaningful differences in functional improvement resulting from OKC of CKC exercises in the early period after ACL-R. Mikkelsen et al. [81] reported there were no significant differences in hamstring torques between an OKC group and an OKC-CKC group. However, the OKC-CKC group had significant increases in quadriceps torque and a significant number of patients that returned to preinjury sports levels. Research by Witvrouw et al. [117–119] also demonstrated no significant difference in most pain and functional measures between OKC and CKC groups for rehabilitation of anterior knee pain.

24.7 Role of Isokinetics in the Clinical Decision-Making Process for Return to Sports

One of the most challenging and yet unsolved dilemmas is what criteria and clinical decision-making should be used for RTP after an ACL-R [22, 56, 57, 81, 120–126]. A few studies [127–131] have identified risk factors for repeat ACL injuries. Paterno et al. [128–131] detected four modifiable risk factors: increased dynamic knee valgus, increased internal rotation ROM of the lower extremity, quadriceps/hamstring muscle imbalances, and balance/proprioceptive deficits. The first three factors demonstrate the isolated triplanar or multiplanar deficits that need to be addressed from a testing and rehabilitation standpoint. Isokinetic testing can help document whether there are dynamic deficits in the muscle's performance and, as well, can be used for velocity-spectrum training of weak muscles.

A team approach is required to assist an athlete to RTP. This includes the physician, physical therapist, certified athletic trainer, certified strength and conditioning specialist, performance enhancement specialist, coaches, technique coaches, sports psychologists, and nutritionists [56]. Unfortunately, even with appropriate surgery and rehabilitation, there is a high reinjury rate [128–131]. The reasons for this are multifactorial; however, it is important to evaluate the testable and trainable modifiable risk factors. Barber-Westin and Noyes [132] performed a systematic review and found the following criteria from 264 studies for RTP: 105 (40%) studies, no criteria; 84 (32%) studies, time postoperative; 40 (15%) studies, time and subjective criteria; and in 35 (13%) studies, objective criteria. In the latter 35 studies, the following objective criteria were used: 9% muscle strength (80–90% of quadriceps and hamstrings), 6% effusion and range of motion, 4% single-leg hop test, 1% stability, and 1% validated questionnaires. There are many considerations that were contained in this systematic review as described above, but there are many other factors that may affect or predict the outcome regarding a successful RTP.

The topic of RTP after ACL injury has seen an explosion in the literature in the last few years [121, 122, 124, 126, 133–139]. However, from a historical perspective, Davies et al. [140, 141] have used a quantitative and qualitative functional testing algorithm (FTA) for the last 37 years through present [56, 57] as a clinical decision-making model for RTP criteria after an ACL injury. The FTA is an objective, quantitative and qualitative, systematic testing and rehabilitation method to safely and rapidly progress a patient from immediate post-injury/postoperative to return to full functional activities and sports. The FTA identifies any particular deficits the patient has so they can be addressed in the rehabilitation programs.

Although a criterion-based approach using a battery of tests are recommended by numerous authors [120, 135, 142], the specific criteria that have predictive validity remains elusive [123]. Initially, patients are stratified into various activity levels including general orthopedic patients, recreational athletes, and competitive athletes. Patients are only tested to the FTA level that represents their activity level.

The FTA is divided into the basic measurements being analogous to impairments of the patient; strength and power testing represents functional limitations, and functional tests reflect functional disability. 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 simultaneously decreasing clinical control. If the patient has a deficit in the testing parameter, then that is where rehabilitation is focused. As an example, if the patient has effusion in the knee, it is not effective to perform strengthening exercises for the quadriceps because of the arthrogenic inhibition of the muscles. The patient is retested after an appropriate time frame, and if they pass the tests, they are then progressed to the next higher level of performance. Often, a minimal deficit may exist and the patient is progressed because realistically, there is always an overlap of the progression of the patient through the rehabilitation program. The FTA data for women is shown below.

- Sport-specific testing
- Lower extremity functional tests (2:00 min)
- Functional hop tests (<10% bilateral comparison, <10% allometric scaling to height [80%], normative data)
- Functional jump tests (<10% allometric scaling to height [90%], normative data)
- OKC isokinetic testing (<20% bilateral comparison)
- CKC isokinetic testing (<30% bilateral comparison)
- Sensorimotor system testing: balance/proprioceptive testing (<10% bilateral comparison with single-leg testing)
- KT-1000/2000 (<3 mm bilateral comparison)
- Basic measurements (<10% bilateral comparison)

We have found we can rehabilitate patients faster than ever because by testing, we always know where the patient is in the rehabilitation program and can focus the interventions specifically on their particular condition and functional status [56, 57]. Although the clinical decision for RTS is certainly multifactorial, the focus of this chapter is on the application of isokinetics in testing and rehabilitation as part of the FTA. One area that is often overlooked in RTS performance testing is to test in a fatigued state. Several studies [143–145] have demonstrated that muscle fatigue decreases performance, and many injuries occur late in games. The area of testing and training in a fatigued state requires further research. Finally, Creighton et al. [146] indicated that if a physician, physical therapist, or athletic trainer returns a patient back to activity and they are reinjured, the clinician may be held liable.

24.8 Summary

This chapter describes the role of isokinetic testing and training after ACL injury and reconstruction, with particular emphasis on the female athlete. The historical perspective of isokinetics development and implementation into testing and training is discussed. An overview of terminology and different assessments is provided for the foundation of understanding the role of isokinetics. The advantages, disadvantages, limitations, indications, and contraindications of isokinetics are described. Isokinetic testing protocols, data analysis and interpretation, and clinical applications for design of rehabilitation programs are included. Specific isokinetic testing for ACL injuries and the correlation to functional performance testing are described. Quadriceps weakness and detailed design of rehabilitation programs with emphasis on the integration of isokinetics are included.

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25

Determination of Neuromuscular Function Before Return to Sports After ACL Reconstruction: Can We Reduce the Risk of Reinjury?

Frank Noyes and Sue Barber-Westin

Abstract

The topic of return to sport (RTS) after anterior cruciate ligament (ACL) reconstruction has become the subject of increased scrutiny as a result of publications citing high reinjury rates upon return to high-risk sports postoperatively, as well as disappointing percentages of athletes who are able to RTS. It is unclear whether reinjuries are due to younger patient age or participation in high-risk activities per se; failure to restore normal neuromuscular indices (to both knees) may be one major source of this problem. A test battery is recommended that measures overall knee and neuromuscular function, along with cardiovascular fitness and core strength. Other common barriers for RTS include psychological factors such as fear of reinjury, anxiety, and depression. Validated questionnaires are provided to measure and detect these issues. A comprehensive RTS decision-based model for sports medicine practitioners is discussed that assesses risk of reinjury from multiple factors and determines the clinician's threshold for acceptable risk. Changes in neurocognitive function and cortical activity that occur after ACL injury and reconstruction, and the potential for screening using validated concussion questionnaires, are discussed. Important preoperative, intraoperative, and postoperative factors that may affect successful RTS are summarized.

25.1 Introduction

The major goals of anterior cruciate ligament (ACL) reconstruction are to restore stability to the knee joint, prevent future injuries, return patients to desired athletic and occupational activity levels, and prevent or delay the onset of knee joint osteoarthritis. Because the majority of patients who undergo this procedure are athletes <25 years of age [1], returning these individuals to their desired sport is a paramount criterion for patient satisfaction [2, 3]. Return to sport (RTS) has become the subject of increased scrutiny as a result of studies reporting high reinjury rates to either knee upon return to high-risk athletics (that require cutting, twisting, and pivoting) postoperatively. In addition, several investigations have reported disappointing percentages of athletes who RTS even though objective testing showed restoration of normal or very good knee function [4–7]. The ability to RTS safely and without subsequent problems of symptoms and limitations is a main motivating factor for athletes to undergo surgery and months of rehabilitation.

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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 (see Chap. 4). In a meta-analysis of data from 19 studies involving 72,054 patients, Wiggins et al. [8] reported, in patients <25 years old, pooled reinjury rates of 21% for the ACL-reconstructed knee and 11% for the contralateral knee. In athletes <25 years of age who returned to high-risk sports involving pivoting and cutting, the pooled secondary ACL injury rate (to either knee) was 23%. In a group of 1415 patients who underwent ACL autograft reconstruction, Shelbourne et al. [9] reported the risk of subsequent injury to either knee was 17% for patients <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.

Dekker et al. [10] 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).

Even though many studies have reported significant correlations of younger patient age and return to high-risk sports with 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. Therefore, reinjuries may not be due to younger patient age or participation in high-risk activities per se; failure to restore these normal indices to both knees may be one major source of this problem.

Several investigations have reported discouraging percentages of athletes who RTS even though muscle strength and neuromuscular function appeared to be restored to normal levels [4–7]. 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 [4]. 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 [7]. 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 [11]. 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.

Common barriers for RTS include psychological factors such as fear of reinjury, anxiety, depression, and preoperative stress [12–22], as well as persistent knee symptoms (pain, swelling, stiffness, instability) [7, 18, 23]. Although not studied extensively, issues related to emotional disturbances (depression, anxiety, fear), motivation, self-esteem, locus of control, and self-efficacy are becoming increasingly important to understand in the overall recovery of ACL injuries [16, 17, 20, 21, 24–27]. Screening, education, and intervention when required may help lessen these psychological barriers to RTS and improve overall outcomes.

Other potential barriers to successful RTS that have received scarce attention are related to changes in neurocognitive function and cortical activity that occur after ACL injury and reconstruction [28–35]. One study detected a relationship between neurocognitive function (reaction times, processing speeds, and scores for visual memory and verbal memory) measured with the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) software and subsequent noncontact ACL injuries [36]. The question of whether modern rehabilitation programs effectively resolve these impairments remains to be answered and should be the subject of increased research attention [37, 38].

25.2 Defining and Measuring Return to Sports

The term RTS has been used to indicate either return to preinjury sports activity levels or return to any type of athletic endeavor. The first RTS Congress involving 17 members of the International Federation of Sports Physical Therapy was held in Switzerland in 2015 [39]. The following consensus statement was made regarding the definition of RTS "… the definition of each RTS process should, at a minimum, be according to the sport…and the level of participation…the athlete aims to return to." There are several validated sports activity questionnaires, and we recommend the use of the Cincinnati Sports Activity Scale (Table 25.1). The Tegner activity score is a frequently used instrument in the sports medicine literature; however, problems can occur in completion of this scale. First, all of the levels are not sorted according to frequency of participation or the intensity of the sport according to 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 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 athletics not listed on the scale, problems may occur when trying to determine which level accurately defines their sport. The Cincinnati Sports Activity Scale allows the analysis of the sport in terms of the requirements of the lower extremity (jumping, pivoting, cutting, running, twisting, turning) and the frequency of participation.

A problem with a strict definition of RTS that includes only patients who returned to preinjury activity levels is that many individuals change their activities due to non-knee-related reasons such as graduation from school, limited time

Table 25.1 Cincinnati Sports Activity Scale

Circle the number which 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, 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, 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, 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

From Barber-Westin et al. [41]

Table 25.2 Change in sports activities

Mark the line which best describes the change you have had in sports activities since your injury or surgery. My sports activities have:
Not changed
—I have no/slight problems
—I have moderate/significant problems
Increased
—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

From Noyes et al. [114]

because of occupational or family commitments, or a loss of interest or motivation. We prefer that the term RTS be used to include all types of sports and recreational activities. A secondary analysis may then determine the percent of a cohort that returned to the same sports activity level and the percent that returned to a different level (Table 25.2). Importantly, we also stress that RTS data should include an analysis of patients who are participating with symptoms (so-called knee abusers [40]). This may be accomplished with use of a symptom rating scale that assesses pain, swelling, and giving-way according to activity levels (Table 25.3) [41]. There is concern of the impact of participating in athletics with symptoms; the long-term effect in terms of increased risk of osteoarthritis needs to be determined.

Table 25.3 Assessment of symptoms according to activity level

Using the key below, circle the appropriate boxes on the four scales which indicates the highest level you can reach WITHOUT having symptoms.

Scale	**Description**
10	Normal knee, able to do strenuous work/sports with jumping, hard pivoting
8	Able to do moderate work/sports with running, turning, twisting; symptoms with strenuous work/sports
6	Able to do light work/sports with no running, twisting, jumping; symptoms with moderate work/sports
4	Able to do activities of daily living along; symptoms with light work/sports
2	Moderate symptoms (frequent, limiting) with activities of daily living
0	Severe symptoms (constant, not relieved) with activities of daily living

1. PAIN

10	8	6	4	2	0

2. SWELLING (actual fluid in the knee, obvious puffiness)

10	8	6	4	2	0

3. PARTIAL GIVING -WAY (partial knee collapse, no fall to the ground)

10	8	6	4	2	0

4. FULL GIVING -WAY (knee collapse occurs with actual falling to the ground)

10	8	6	4	2	0

From Barber-Westin et al. [41]

25.3 RTS Models: How Is the Decision Made to Release Athletes to Unrestricted Activities?

The first comprehensive RTS decision-based model for sports medicine practitioners was published in 2010 by Creighton et al. [42] and later modified in 2015 by Shrier [43]. Known as the Strategic Assessment of Risk and Risk Tolerance (StARRT) framework, this model assesses risk of reinjury from multiple factors and determines the clinician's threshold for acceptable risk (Table 25.4).

A consensus statement was published in 2012 from ten surgeons (representing six major professional associations) regarding the RTS decision-making process [44]. It was deemed essential that the team physician confirm:

- Restoration of sports-specific function to the injured part
- Restoration of musculoskeletal, cardiopulmonary, and psychological function, as well as overall health of the athlete
- Restoration of sport-specific skills
- Ability to perform safely with equipment modification, bracing, and orthoses
- The status of recovery from the acute or chronic problem and associated sequelae
- Psychosocial readiness
- Athlete poses no undue risk to themselves or the safety of other participants
- Compliance with federal, state, local, and governing body regulations and legislations.

Table 25.4 The Strategic Assessment of Risk and Risk Tolerance (StARRT) framework for return to sport decision-making

Step #	Factors
1. Assessment of health risk	Patient demographics (age, gender) Symptoms Medical history (previous ACL injury either knee) Signs on physical examination Medical tests (X-ray, MRI)
2. Assessment of activity risk	Type of sport (contact, noncontact) Position played Limb dominance (symmetry) Competitive level Ability to protect Functional tests Psychological readiness
3. Assessment of risk tolerance (clinician's threshold for acceptable risk)	Timing and season (preseason, playoffs) Pressure from athlete External pressure (coach, family) Masking the injury Conflict of interest (financial) Fear of litigation (if restricted or permitted)

From Shrier [43]

Blanch and Gabbett [45] discussed the problem of failure to ascertain if the athlete's training history was sufficient to be ready for the demands of full competition. The recommendation was made to include an acute:chronic workload ratio in the RTS decision process. A series of studies involving cricket, rugby, and Australian football demonstrated that when an athlete's training and playing load for a given week (acute load) spiked above what they had been doing on average over the past 4 weeks (chronic load), they were more likely to be injured ($R^2 = 0.53$). The acute:chronic ratio could be used to determine load progression during the latter phases of rehabilitation after ACL reconstruction and, as well, when the athlete gradually resumes sports activities. Morrison et al. [46] detailed practical sports conditioning training methods and monitoring guidelines for acute:chronic workload to assist in this process.

Ardern et al. [39] recommended using models that consider biological, psychological, and social factors that influence RTS decisions. A biopsychosocial model was developed that included injury characteristics, physical factors, psychological factors, social/contextual factors, and functional performance as related to RTS. These recently developed RTS models hold promise but require validation in large cohorts to determine if their usage will result in a decrease in reinjury rates (to either knee) in ACL-reconstructed patients.

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 [47]. There were 264 studies included, of which 105 (40%) failed to provide any RTS criteria. In 84 studies (32%) the amount of time postoperatively was the only criterion provided. In 40 studies (15%) the amount of time along with subjective criteria were given. 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. More recently, other authors have agreed and published recommendations of objective tests including isokinetic muscle assessments, single-leg function (hop tests, stability tests), and overall alignment on drop-jump and single-leg squatting [6, 23, 48–67]. In a systematic review of 88 studies involving 4927 patients, Abrams et al. [68] noted that single-leg hop tests and isokinetic strength measurements were the most commonly used measures to determine RTS readiness after ACL reconstruction.

Chapter 22 details our postoperative rehabilitation program. We advocate neuromuscular retraining before patients are released to unrestricted high-risk athletics [47, 69–71]. Specific goals are provided in Chap. 22 to begin the running and agility program, basic plyometric training, and advanced neuromuscular retraining. The running and agility program is usually begun 16–20 weeks postoperatively and is designed based on the patient's athletic goals. Basic plyometric training is advocated for all athletes, and advanced neuromuscular retraining is recommended for those who wish to return to high-risk sports. Our recommendations and criteria for unrestricted RTS are detailed next.

25.4 Testing to Determine Function

25.4.1 Knee Examination by Physician

Before testing begins, our athletes undergo a comprehensive examination that includes Lachman, pivot-shift, and KT-2000 testing (134 N total anteroposterior displacement). Assessment is made of any knee joint effusion, patellofemoral problems, and range of motion (ROM). Criteria to undergo neuromuscular testing are:

- Lachman: grade 0–1, IKDC rating of normal or nearly normal
- Pivot-shift: IKDC rating of normal or nearly normal
- KT-2000: ≤3 mm difference between knees
- No effusion
- ROM: IKDC rating of normal or nearly normal
- No patellofemoral pain, no or mild crepitus, and no instability
- Normal body mass index

25.4.2 Overall Neuromuscular Function

We recommend the video drop-jump test [72] and the single-leg squat test [73] to assess overall lower limb alignment in the coronal plane. These tests are detailed in Chap. 16. The goal for the drop-jump test is ≥60% normalized knee separation distance (if software is available); otherwise, a subjective analysis of the video should demonstrate no valgus collapse and knees flexed for a controlled landing. The single-leg squat is done five consecutive times and should demonstrate no valgus collapse, medial-lateral movement, or pelvic tilt (see also Chap. 13). Perform at least two validated single-leg hop tests (single hop, triple hop, triple crossover hop, timed hop [74], see Chap. 16); the goal is ≤15% deficit in limb symmetry.

25.4.3 Muscle Strength: Lower Extremity, Core

Quadriceps and hamstring strength and endurance should be tested with isokinetic equipment if possible. We recommend 180 and 300°/s test speeds, and there should be ≤10% deficit compared with the contralateral side prior to release to unrestricted activities. A portable fixed or handheld dynamometer may be used to test isometric strength of the quadriceps in 60° of flexion and the hamstrings at 60° or 90° of flexion. If these equipments are not available, a 1-repetition maximum bench press and leg press are recommended. There are a variety of measures to assess core strength, including the 60-s sit-up test (see Chap. 16).

25.4.4 Video Plant and Cut Assessment

We recommend an assessment of the athlete's hip and knee flexion and posture during a preplanned plant and cut drill. This test is done as described by Pollard et al. [75] where the athlete runs 5 m to a spot designated on the floor with tape, plants on the reconstructed 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°. A subjective analysis of the videotape is done, with the goals of hip and knee flexion close to 60°, an upright posture with no leaning or rotation, foot placement close to the midline of the body, no hip adduction or internal rotation, and no knee valgus collapse during the cut.

25.4.5 Cardiovascular Fitness

Estimated aerobic capacity may be measured using either the multistage fitness test or the Yo-Yo intermittent recovery test, described in detail in Chap. 16.

25.5 Determining Psychological Readiness to Return to Sport

Psychological factors such as fear of reinjury, anxiety, depression, and preoperative stress are common barriers to RTS and overall patient satisfaction after ACL reconstruction [3, 12–21]. Several validated questionnaires may be used to determine an athlete's psychological status both before surgery and postoperatively (Table 25.5).

Table 25.5 Validated psychological questionnaires

Questionnaire	Items assessed	Scoring
ACL-quality of life [76]	– Symptoms, physical complaints – Work-related items – Recreational activities and sports participation – Lifestyle – Social and emotional feelings	100-mm visual analogue scale
ACL-Return to Sports After Injury [77]	– Emotions – Confidence in performance – Reinjury risk appraisal	12 items 10-point increments
Knee Self-Efficacy Scale [78]	– Daily activities – Sports and leisure activities – Physical activities – Knee function in the future	22-items 11-point Likert scale
Tampa Scale for Kinesiophobia [79, 80]	– Fear of movement/reinjury	17 items 4-point Likert scale
Tampa Scale for Kinesiophobia Modified [81]	– Fear of movement/reinjury	11 items 4-point Likert scale
Injury-Psychological Readiness to Return to Sport Scale [82]	– Confidence in ability to play, performance	6 items 10-point increments
Reinjury Anxiety Inventory [83]	– Anxieties about rehabilitation and return to sport	28 items 4-point Likert scale
Quick Inventory of Depressive Symptomatology [84]	– Depression – Sleep – Appetite/weight	16 items 4 responses for each item

Fear of reinjury has been cited by multiple studies as a primary reason for failure to RTS or to the athlete's desired level of competition [4, 12, 14, 17–20, 22, 27, 79]. In a meta-analysis of 69 articles involving 7556 patients, Ardern et al. [4] reported that although 81% returned to some type of sports activity, only 65% returned to preinjury levels and 55% returned to competitive sports. These authors reported moderate to large effects sizes (0.7–0.9) regarding fear of reinjury; athletes with lower scores regarding fear had significantly better outcomes regarding return to preinjury sports levels [4, 12]. In addition, a large effect size (0.9) was reported for athletes with greater psychological readiness to return to previous sport levels. Reinjury anxiety was associated with heightened concerns for RTS in a series of 335 athletes who had sustained an injury preventing participation for at least 4 weeks [85]. Fear of reinjury may be determined using scales such as the ACL-Return to Sports After Injury (ACL-RSI) scale (Table 25.6) and the Tampa Scale for Kinesiophobia (TSK, Table 25.7), and reinjury anxiety may be measured using Walker et al.'s Reinjury Anxiety Inventory [83].

Table 25.6 ACL-Return to Sports After Injury (ACL-RSI) scale questions[a]

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 re-injuring your knee by playing 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 areanswered by circling one number from 0 to 10, where 0 = not at all and 10 = extremely. Scores for all questions are summed and then divided by 120 and multiplied by 100

[a]From Webster et al. [77]

Table 25.7 Tampa Scale for Kinesiophobia (TSK)

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. Simply 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

From Vlayeyn [80] and modified by Kvist et al. [79] for knee injuries

Athletes who sustain ACL injuries have reported higher levels of depression compared with uninjured athletes [86]. The effects of depression on outcomes 1 year after ACL reconstruction were determined by Garcia et al. [26]. In a group of 64 adult patients, 27 (42%) were diagnosed with depression before surgery using the Quick Inventory of Depressive Symptomatology (scores ≥6 points; Table 25.8). Preoperatively, this group had significantly lower mean IKDC and Lysholm scores than the remainder of the cohort. At follow-up, the group diagnosed with depression had a higher incidence of complications. Although IKDC and Lysholm

Table 25.8 Quick inventory of depressive symptomatology

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
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 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

(continued)

Table 25.8 (continued)

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 or finish my usual daily activities (e.g., 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
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

scores were similar between groups at 6, 12, and 24 weeks postoperative, at 1 year, the depressed group's scores were significantly lower (IKDC, 71.8 and 89.3 points, respectively, $P < 0.01$; Lysholm, 75.2 and 88.4 points, respectively, $P < 0.05$). Because of the high number of patients diagnosed with depression, the authors recommended future screening and appropriate management of this disorder.

High scores of perceived self-efficacy measured preoperative (confidence in a successful recovery) were found in one study to be predictive of physical activity 1 year postoperatively [87]. This investigation developed and tested the Knee Self-Efficacy Scale (Table 25.9). Subsequently, Ardern et al. [24] used this questionnaire (along with the TSK and ACL-RSI) 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. Others have reported associations between psychological factors (perceived ability and benefit of returning to sport) measured preoperatively and postoperative RTS rates [88–90]. Clinicians should consider using psychological questionnaires preoperatively and as part of the RTS process to determine if intervention is required [17]. Future studies are required to more thoroughly investigate the appropriate identification and management of psychological and psychosocial disorders after ACL injury and reconstruction [20, 21, 91].

Table 25.9 The Knee Self-Efficacy Scale

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
From Thomee et al. [78]

25.6 Neurocognitive Testing

There are several factors that influence neuromuscular control required for athletic activities, including proprioceptive, kinesthetic, visual, and vestibular sensory sources in addition to cortical and spinal motor commands [35, 36]. Understanding the brain's role in both noncontact ACL injury research and advanced rehabilitation required to restore complex sensory integration and motor planning is of paramount importance [28–35, 92, 93].

ACL deficiency led to alterations in several sensorimotor cortical areas in a group of 17 patients compared with noninjured controls during a simple flexion-extension task detected with magnetic resonance imaging (MRI) [31]. Investigators reported alterations in cortical activity in ACL-deficient patients during a knee-angle reproduction task [28] and during reproduction of 50% of a maximum voluntary isometric quadriceps contraction [29]. A recent study in 37 healthy athletes found a direct association between poor performance on a computerized neurocognition test (Concussion Resolution Index [CRI]) and an increase in risk factors on a reactive drop-jump test [94]. Compared with those with high CRI scores (mean, 78th percentile), athletes with low CRI scores (mean, 41st percentile) had significantly greater peak vertical ground reaction forces (1.81 ± 0.53 BW and 1.38 ± 0.37 BW, respectively, $P < 0.01$), peak anterior shear forces (0.91 ± 0.17 BW and 0.72 ± 0.22 BW, respectively, $P < 0.01$), knee abduction moments (0.47 ± 0.56 BW × ht. and 0.03 ± 0.64 BW × ht., respectively, $P < 0.05$), and knee abduction angles on landing (6.4 ± 4.7° and 1.3 ± 5.6°, respectively, $P < 0.05$). There are several computerized neurocognition tests currently available, including:

- ImPACT (ImPACT Applications, Pittsburgh, PA)
- ANAM4 (Automated Neuropsychological Assessment Metrics, Vista Life Sciences, Parker, CO)
- Axon Sports CogState Test (CogState Ltd., Melbourne, Australia)
- CNS Vital Signs (Morrisville, NC)
- CRI (Headminder, New York, NY)

A recent meta-analysis conducted by Farnsworth et al. [95] revealed that the Axon test had the highest proportion of acceptable outcomes and shorter test duration of the five tests listed above. Resch et al. [96] assessed the reliability of the ANAM, CNS, and ImPACT in healthy college students over three time points (baseline, 47 days later, and then 7 days later). Overall, measures of reaction time and information processing had the highest intraclass correlation coefficients values and measures of memory had the lowest. The authors were unable to provide definitive recommendations for the use of one test compared with the others. The ImPACT test has received the most attention in the literature; scores remain relatively unchanged in healthy high school athletes over time [97] and have acceptable long-term reliability in professional ice hockey players [98], youth ice hockey players [99], and collegiate students [100]. According to ImPACT.com, this test is used in over 7400 high schools, 1000 colleges and universities, 900 clinical centers, 200 professional teams, and select military units [101]. As noted by Herman and Barth [94], because of the existing widespread use of this (and other) neurocognitive tests to obtain baseline data in athletes, it may be possible to use this information in ACL injury risk assessment models. Further research is required to provide definitive recommendations regarding which of the available tests is most valid for ACL-reconstructed patients for RTS screening.

25.7 Spectrum of Optimal Treatment of Complete ACL Injuries in Athletes

There are several important preoperative, intraoperative, and postoperative factors that play a role in RTS after surgery. Investigators have noted no benefit [102, 103] and, in some cases, deleterious outcomes [104, 105] when ACL reconstruction is performed before the resolution of limitations in knee motion, muscle atrophy, swelling, and pain from the injury. Investigators have heavily emphasized the need to restore normal knee motion when possible before surgical intervention [104, 106–108]. The exception is the presence of a mechanical block to extension, such as a bucket-handle meniscus tear [109]. Preoperative rehabilitation is therefore recommended to resolve pain, effusion, and swelling, promote full ROM, and restore neuromuscular function, muscle strength, and normal gait indices.

Intraoperatively, anatomic tunnel placement and secure internal fixation are crucial to ensure optimal graft healing [110]. We prefer a bone-patellar tendon-bone autograft for athletes and do not recommend allografts because of increased failure rates in younger athletic populations [111–113].

We developed two postoperative rehabilitation protocols (Chap. 22) that are based on 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. 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. These risks cannot be predicted and patients are cautioned to return to strenuous activities carefully and avoid any activity in which pain, swelling, or a feeling of instability develops. The early RTS is not encouraged 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 MRI or arthroscopic evidence of major bone bruising or articular cartilage damage exists.

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Part V

Future Directions

26

Promotion of ACL Intervention Training Worldwide

Sue Barber-Westin and Frank R. Noyes

Abstract

This chapter discusses the need to adopt a public health approach in order to achieve the successful widespread implementation of ACL intervention training programs. This approach involves using epidemiologically based research methods and models designed to evaluate the public health significance of injuries and the feasibility and outcomes of prevention programs. These models attempt to determine the outcome of a program from the viewpoint of both the participants and settings (organizations), along with the ability to deliver the intervention to large numbers of people across different regions for a long period of time. Sports injury prevention models are presented that should be taken into consideration for future use. Studies that have addressed the knowledge and attitudes of athletes and coaches toward injury prevention training are summarized.

26.1 Introduction

Prevention of sports medicine injuries has long been established as vital to athletes of all ages, skill levels, and motivations. In 1970, Haddon [1] presented ten strategies that were later described as a matrix for preventing human and economic losses. These strategies sought to highlight and recommend preventative efforts instead of the more common reactive efforts that focused only the treatment of injuries or damage to either people or property.

In today's world, the need for continued work in identifying modifiable and non-modifiable risk factors for noncontact anterior cruciate ligament (ACL) injuries using multivariate models is evident (see Part II) [2–5]. The development of an athletic profile using clinically feasible, cost-effective methods that would allow identification of individuals (both female and male) who are at increased risk for injury continues to be under study. Even with these considerations, evidence exists that certain ACL injury intervention programs are effective in both reducing the incidence of injury and enhancing athletic performance indices [6–8]. Programs that focus on neuromuscular retraining for landing, cutting, and pivoting, as well as strengthening and dynamic balance, can successfully improve biomechanical variables believed to contribute to ACL injury [3, 9]. With the well-known inherent problems that

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accompany ACL ruptures and the potential for premature osteoarthritis, we believe that the widespread implementation of neuromuscular retraining programs is indicated, even while we continue to study the causes and risk factors of these injuries. This process involves education of athletes, parents, coaches, and school administrators on the importance of knee injury prevention and the benefits of participation in an intervention program with documented evidence of success. Other professional health caregivers, such as primary care physicians and pediatricians, need to be involved in order to be able to use screening procedures during sport pre-participation physical examinations and encourage injury prevention training in female athletes. As well, health promotion epidemiological measures and models for assessing implementation of the intervention are required to determine if the program has a realistic chance of succeeding over a wide region and for a long period of time.

Although there have been several randomized, controlled trials that measured the effectiveness of ACL injury prevention programs, there have been few implementation studies which considered the impact of the interventions in a real-world, uncontrolled setting [10]. And, while some ACL programs have proven to be effective in reducing the injury rate, several interventions have had limited or no success that has been attributed to poor compliance, subject boredom, or inability of the program to achieve improvements in neuromuscular indices [11]. There exists the need to conduct well-designed large-scale studies that can shed light on the ability of healthcare professionals, coaches, and trainers to provide this intervention based on a public health approach [12–18].

Critical Points

- Development of profile using clinically feasible, cost-effective methods that identify individuals at increased risk for ACL injury is paramount.
- Authors believe widespread implementation of ACL intervention programs indicated.
- Few implementation studies done to date assess the impact of ACL interventions in a real-world, uncontrolled setting.
- Well-designed, large-scale studies required determine the ability of healthcare professionals to provide intervention programs based on a public health approach.

26.2 A Public Health Approach to ACL Intervention Programs

26.2.1 Background

A public health approach toward ACL intervention training involves using epidemiologically based research methods and models designed to evaluate the public health significance of injuries and the feasibility and outcomes of prevention programs [19]. A cost-effectiveness analysis reported that universal neuromuscular training of all young athletes was the best strategy for preventing ACL injuries compared with universal screening and training of only identified high-risk athletes [20]. The health consequences of ACL injuries in young athletes include lost time in school, decreased grade point averages, loss of collegiate scholarships, and premature osteoarthritis (see Chap. 2). As well, athletes may suffer psychological changes (anger, depression, loss of confidence) following ACL injury and reconstruction [21–23]. Current trends of inactivity, lack of physical education classes in US schools, and obesity are of concern in regard to motor skill development and prospective ACL injury risk. The cost of an ACL rupture is substantial; the mean lifetime cost to society for a patient undergoing ACL reconstruction was estimated in one study to be $38,121, while the mean cost for rehabilitation only was $88,538 [24]. All of these problems qualify ACL injuries as a public health concern.

In order to appropriately measure the ability of an intervention to succeed in a widespread manner, evaluation models (or frameworks) have been designed for injury prevention research [25]. These models attempt to determine the outcome of a program from the viewpoint of both the participants and settings (organizations), along with the ability to deliver the intervention to large numbers of people across different regions for a long period of time. There is a valid need to improve our understanding of the factors that influence the successful implementation of ACL intervention programs and move toward offering these programs in community settings. The use of models designed by epidemiologists is an important step in advancing the dissemination of knowledge and intervention techniques for ACL injury prevention.

The first injury prevention model designed specifically for sports was described by van Mechelen et al. [26] in 1992. This was followed by a framework published in 2006 by Finch [10] who recommended a broader approach be used than that previously recommended for sports injury prevention studies. Emphasis was placed on the importance of researchers understanding implementation issues and developing strategies to initiate and evaluate intervention programs in "real-world" settings. Van Tiggelen et al. [27], Finch and Donaldson [13], and Vriend et al. [25] contributed additional models for consideration.

In addition, behavioral and social science theories and models (BSSTM) have been designed and used to measure health and safety issues, including uptake and maintenance of injury prevention measures [28, 29]. To date, BSSTM have not been routinely used in the development or measurement of sports injury prevention research interventions [28]. McGlashan and Finch [28] noted the overall lack of usage of BSSTM by injury prevention researchers. Their systematic review of 100 sports injury prevention articles showed that only 11 used these theories or models to guide program design and implementation or measure a theory or construct. Because prevention of sports injuries is a multifactorial process, these authors noted that successful implementation of a program must address the sports culture and player behaviors, along with the efficacy of the intervention. The success of intervention programs to reduce the incidence of injury depends in part on modification or change in the behaviors and attitudes of players and coaches. Therefore, the application of models such as the Health Belief Model [30], the theory of planned behavior [31, 32], and the diffusion of innovation theory [33] in future sports injury prevention research is well indicated.

26.2.2 Injury Prevention Outcome Models

26.2.2.1 TRIPP Framework

The Translating Research into Injury Prevention Practice (TRIPP) is a sports injury research framework that is directed toward understanding the implementation aspect of sports injury prevention, as well as building an evidence base for the program's effectiveness [10]. The model comprises six stages:

1. Conduct injury surveillance.
2. Establish etiology and mechanisms of injury.
3. Develop prevention measures.
4. Study intervention under ideal conditions, and perform scientific evaluation.
5. Describe intervention context to inform implementation strategies.
6. Evaluate effectiveness of prevention measures in implementation context.

In developing this model, Finch [10] stressed that implementation research is necessary to ensure that injury prevention methods and programs are adopted by the sports community. The author's experience demonstrated that athletes and sports clubs are supportive of intervention research if they are fully informed, if the intervention techniques are adoptable, and if safety is a major concern for their sport or club. Other motivators for injury prevention training include the use of the intervention by peers and role models, professional promotion targeted to specific sports, and other benefits derived from training such as performance enhancement.

26.2.2.2 Van Tiggelen Model

An expansion of the TRIPP model was proposed by Van Tiggelen et al. [27] in order to account for risk-taking behavior and compliance of the individual athlete (Fig. 26.1). Although developed for overuse injuries in both the workplace and athletics, this model could be used for any sports injury prevention program to determine its overall effectiveness and potential for widespread implementation. The model introduces new steps which are done after the efficacy of the intervention has been proven. These include:

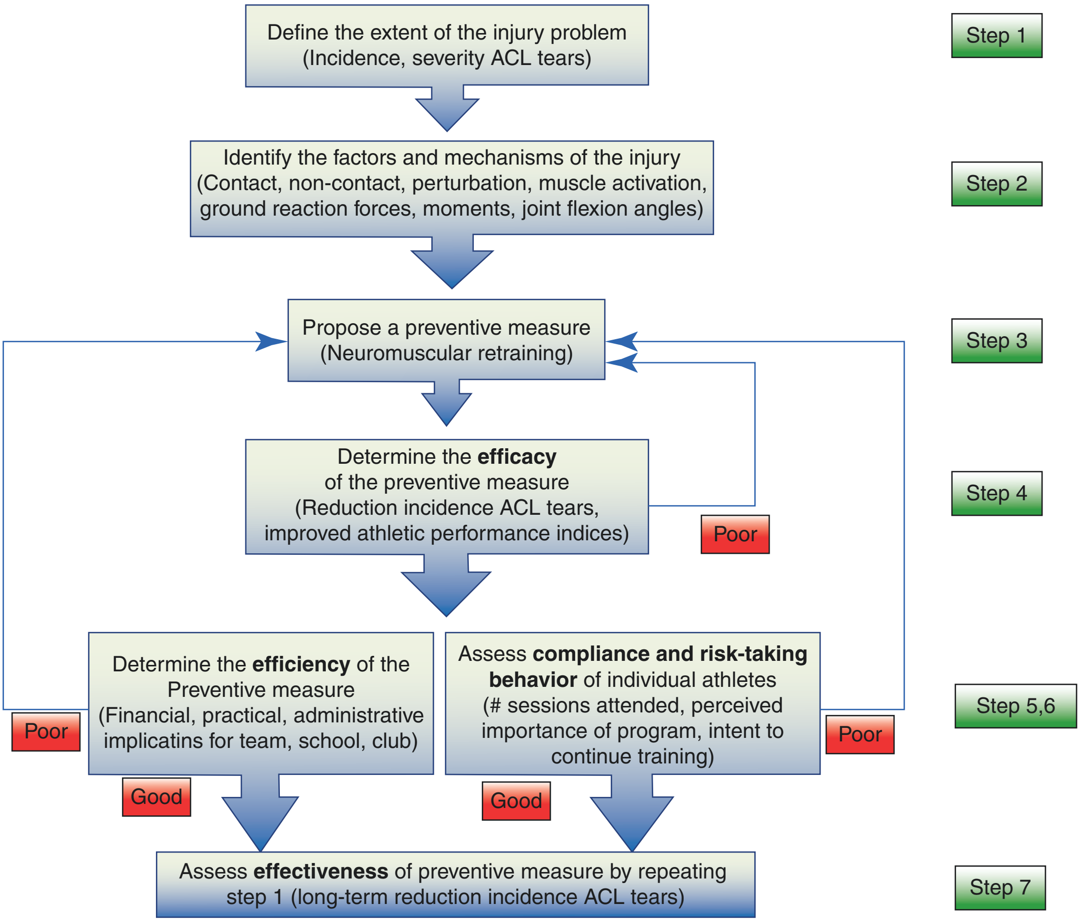

Fig. 26.1 Sequence of prevention of overuse injuries proposed by Van Tiggelen et al., with ACL injury intervention used as an example [27]

- Assessment of the efficiency of the program for the organization, league, school, or club in terms of financial, administrative, and personal resources. A cost analysis must determine that the reduction in injury risk does not exceed available resources.
- Determine the compliance level for the intervention.
- Determine the risk-taking behavior of the individual athlete.

According to Lund and Aaro [34], four factors influence the modification of attitude, behavior, and structural conditions to prevent injuries. These are behavior, physical and organizational environment, attitudes and beliefs, and social norms/culture. Evidence exists that simply possessing knowledge will not directly affect behavior; even though an athlete may be aware of the risk of sustaining an ACL injury during soccer, she may still not wish to undergo an intervention to lessen this risk. This is especially true if her peers and coach do not believe that the intervention will be effective. Van Tiggelen et al. [27] noted that the most appropriate way of achieving behavior modification (i.e., changes in neuromuscular indices to reduce the risk of an ACL injury) is to integrate the intervention program into an athlete's regular training routine rather than in a dictatorial or completely separate fashion. In this manner, the intervention exercises are an accepted part of the athlete's or team's standard methods of training.

26.2.2.3 RE-AIM Framework

In order to study the ability of an intervention program to be effective in public health settings, Glasgow et al. [35] developed the RE-AIM model. Using findings only from rigorous interventions tested in highly motivated subjects under controlled conditions as a basis for widespread implementation of an injury prevention program is problematic. The ability to recreate the intervention in uncontrolled circumstances with limited staff and resources, and less motivated subjects, may not be possible. The RE-AIM model measures the impact of an intervention by rating variables in five categories (Table 26.1). Each category may be comprised of a single question or a series of questions, based on the study.

- Reach: a measure of participation of a defined population
- Efficacy: assessment of both positive and negative outcomes of a program
- Adoption: proportion of a population and caregivers that will use or try out a program
- Implementation: the extent to which a program is delivered as intended
- Maintenance: the extent to which a program becomes routine and part of the everyday culture or practice training

The RE-AIM model has been used to evaluate a tai chi program to prevent falls in the elderly [36], exercise programs for arthritis [37], and intervention training programs for lower limb injuries [38]. Table 26.2 shows the variables that were measured in the model's categories and results for the tai chi program investigation [36]. The use of this model allowed recommendation of this program based on the achievement of high scores in all of the categories.

O'Brien and Finch [39] used a modified version of this model to identify implementation components of injury prevention programs (in team ball sports) that influence the adoption, execution, and maintenance of the programs. The model allowed a systematic review of 60 publications that determined mean values for efficacy (58%), reach (34%), adoption-setting level (1%), adoption-delivery agent level (7%), implementation (36%), and maintenance individual level (1%).

Table 26.1 The RE-AIM model evaluation dimensions [35]

Category	Description	Level
Reach	Proportion of the target population that participated in the intervention, i.e., participation rates	Individual
Efficacy	Success rate if implemented as in guidelines; defined as positive outcomes minus negative outcomes	Individual
Adoption	Proportion of settings, practices, and plans that will adopt this intervention	Organization
Implementation	Extent to which the intervention is implemented as intended in the real world	Organization
Maintenance	Extent to which a program is sustained over time	Individual and organization

Table 26.2 Use of the RE-AIM model to evaluate a tai chi program to prevent falls in the elderly [36]

Category	Variables measured	Results
Reach	No. of eligible subjects who responded to the program promotion (6 senior centers in 5 cities) × 100	Reach = 87% Participation eligible subjects = 89%
Efficacy	Functional reach test, Up and Go test, time to rise from a chair, 50-ft speed walk, Short-Form 12-item physical and mental health summary scale, no. of falls per month	Significant improvements all measures, $P < 0.001$
Adoption	Percentage of local senior centers approached that agreed to participate and implement program	100%
Implementation	Extent to which providers/instructors implemented key elements of program, including schedule, class attendance ≥75%, average ≥ 30 min in-home practices/week	Program = 100% Average class attendance, 80% Average time at home, 32 min
Maintenance	Center's willingness to consider program part of their programs, continue program after completion of intervention. Participants continue tai chi practice for 12 weeks after class termination	Centers = 100% Participants = 92%

26.2.2.4 RE-AIM SSM Framework

Finch and Donaldson [13] presented an extension of the RE-AIM model as a proposed method of evaluating sports injury intervention programs, termed the RE-AIM Sports Setting Matrix (RE-AIM SSM). This extended model identifies where each of the RE-AIM dimensions may be assessed across the sports delivery hierarchy, including national, state, and regional organizations, leagues, clubs, teams, and individual participants. These authors stressed that a successful knee injury intervention program relies heavily on the structures and background activities in place to support delivery of the training. This includes appropriate training of coaches so that the scientific basis and rationale and intervention methods are completely understood. Coaches need to be able to build the program into either their preseason or in-season regular training schedule and ensure the program is delivered in the manner in which it was intended. Facilitation of this type of implementation on a wide scale will require higher-level sources of funding, support, and preferably endorsement from either a state or national sporting organization.

The RE-AIM SSM was used to evaluate the implementation of Walden's knee injury prevention program [40]. Items considered relevant and applicable from the model were selected as shown in Table 26.3 [41]. The study found high

Table 26.3 Use of the RE-AIM SSM to evaluate a neuromuscular training program [41]

RE-AIM SSM dimension	Target group			
	National	District	Trial coaches	Current coaches
Reach			Knowledge of program (control group)	Knowledge of program
Effectiveness			Perceived effect in reducing acute knee injuries and enhancing performance and satisfaction with the program Complaints about the program from players Complaints about the program from parents	Perceived effect in reducing acute knee injuries and enhancing performance and satisfaction with the program
Adoption			Frequency with which coaches carried on using the program (intervention group) or started using it (control group) after 2009	Use of the program
Implementation			Fidelity with the program (number of exercises)	Participation in education and training in the program Fidelity with the program (dosage and number of exercises)
Maintenance	Presence of policies for program implementation and use with female adolescent players Annual education and training for coaches and physical therapists (2010–2012)	Presence of policies for program implementation and use with female adolescent players Annual education and training for coaches and physical therapists (2010–2012)	Use of the program over time (2010–2012) Intention to continue using the program	Delivery of education via the club Presence of formal guidelines within the club

reach and adoption rates of the program, but low scores were noted for program fidelity, with approximately three-quarters of coaches reporting they trained less than the recommended frequency or had modified the program's content.

In order to continue to understand the complexities involved with implementation of sports injury prevention programs on a widespread basis, Finch and Donaldson [13] also proposed that these types of questions should be asked:

- What are the actual behaviors of the participants (high-risk versus low-risk athletes)?
- Are participant/instructor attitudes and knowledge favorable?
- What would make people/communities more or less likely to adopt a program?
- What setting/cultural delivery factors are also important?
- What infrastructure support is needed in the setting?
- What are the factors that will influence the sustainability of interventions over a long period of time?

26.2.3 The Health Belief Model

The Health Belief Model (HBM) was developed in the early 1950s by social psychologists at the US Public Health Service. The components of the model were derived from psychological and behavioral theories in an attempt to explain "the widespread failure of people to accept disease preventives" [42]. The HBM consists of four dimensions:

1. Perceived susceptibility: beliefs about the risk of being injured
2. Perceived severity: beliefs about the seriousness of an injury in terms of health and sporting consequences
3. Perceived benefits: beliefs about the effectiveness of interventions available to reduce injury risk
4. Perceived barriers: beliefs about the negative aspects of a prevention measure, including expense, time commitment, and convenience

In addition, the model includes two other dimensions: cues to action, or factors that would motivate an athlete to participate in an injury intervention program, and self-efficacy, or an athlete's belief in their ability to participate in injury prevention training. The HBM and RE-AIM frameworks were used to develop a questionnaire that assessed the attitudes and beliefs of Australian football players regarding lower limb injuries, risk factors, and intervention programs [43].

Critical Points

- Public health approach uses epidemiologically based research methods and models to evaluate public health significance of injuries and feasibility of prevention programs.
- Health consequences of ACL injuries well recognized.
- Evaluation models (or frameworks) designed for injury prevention research:
  - Translating Research into Injury Prevention Practice (TRIPP)
  - Van Tiggelen model
  - RE-AIM framework: reach, efficacy, adoption, implementation, maintenance
  - RE-AIM SSM framework: assesses model across sports delivery hierarchy
  - Health Belief Model beneficial to study beliefs and attitudes of athletes and coaches regarding injury risks and intervention training

26.3 Knowledge and Attitudes of Coaches Toward Injury Prevention

The dissemination of current knowledge regarding the gender disparity in ACL injuries, intervention principles to reduce this problem, and potential athletic performance improvements that may be achieved through comprehensive training programs to individuals involved with female athletes at various institutions is crucial. One element for the successful widespread implementation of ACL intervention training is the education of high school and collegiate coaches, strengthening and conditioning specialists, athletic trainers, athletes, parents, and administrators (see also Chap. 27). It is important that the devastating short- and long-term consequences of ACL injuries, along with the potential to reduce their incidence in female athletes, be explained with a scientific basis and high-quality research to support recommendations.

Because coaches are frequently responsible for the development and implementation of training and conditioning programs for players, their qualifications and knowledge are important in influencing injury risk [44, 45]. Research has demonstrated that behavior change interventions for children and adolescents are more effective when adult role models are involved [46]. Unfortunately, insufficient training of coaches and poor teaching techniques are associated with higher injury rates [47, 48]. Educating and convincing athletes to participate in ACL injury intervention training can be difficult, especially if the coach does not believe these programs are beneficial.

Saunders et al. [49] sought to determine the perceptions of 24 coaches of a 6-week lower limb intervention program that they delivered to junior netball players. In addition, recommendations from coaches for improving the implementation of the program were analyzed. The RE-AIM framework was used to evaluate these variables (Table 26.4). A total of 31 coaches attended a 1-h education workshop in which the rationale and components of the program were provided. Of these, 24 completed a feedback survey 17 weeks after they had completed the intervention. The reach dimension of the RE-AIM of the program was 50% for both coaches and players involved in the netball association. The effectiveness, rated using three factors, ranged from 79% to 88%. The coaches completed questionnaires regarding factors or circumstances which made training difficult and the preferred methods to learn the program. The study found that 63% of the coaches believed that the time required for training was a problem, and 83% of the players were unmotivated or had difficulty paying attention to the exercises. A training manual was identified by 96% of the coaches as an important educational resource. There were limitations to the study, such as no information was provided on the seven coaches who attended the workshop but did not complete the follow-up survey and no demographic data were provided for the players (reach dimension exposure and demographic data). Even so, this study demonstrated the successful use of the RE-AIM model to study the effectiveness and feasibility of a lower limb injury prevention program.

Frank et al. [50] used the constructs of the RE-AIM SSM to evaluate the effects of an ACL injury prevention program workshop held for 34 soccer coaches of female elite youth teams. The coaches were surveyed before and after the workshop regarding their knowledge and attitudes toward conducting a warm-up neuromuscular training program. The subsequent adoption and implementation of the program were then tracked

Table 26.4 Application of the RE-AIM framework in the evaluation of a coach-led lower-limb injury prevention training program in junior netball players [49]

RE-AIM category	Variables measured	Results
Reach	Exposure of program to coaches and players, and subsequent players, within the netball organization	50% coaches
		50% players
Effectiveness	% of coaches who believed program was effective in:	
	– Improving correct landing technique	88%
	– Reducing lower limb injury risk	79%
	– Improving performance measures	83%
Adoption	Coaches' responses on facilitation adoption of program, most relevant age group, and skill level	U13, U15, low-skilled players benefit the most
Implementation	Coaches' opinions on resources to improve implementation	See article
	Factors or circumstances identified as challenges for implementing program	See article
	Number coaches providing constructive feedback on program	77%
Maintenance	Number coaches who intend to use program with players in the future	88%

during the following season. Although the workshop was effective in improving attitudes regarding the advantages of training, only 53% of the club's teams used the program, and there was high variability in compliance.

A survey of 66 high school soccer and basketball coaches in Oregon demonstrated that, although 52% reported being aware that injury prevention programs were scientifically proven to reduce the risk of injury, only 21% were using a program and only 9% were using the program exactly as designed [51]. Barriers to program utilization were perceptions that injury prevention programs offered little advantages over current team practices, lower extremity injuries were not a substantial problem, practice time was limited, and players had negative attitudes toward training.

The factors that influenced implementation of ACL prevention training in women soccer coaches for players aged 11–22 years were determined by Joy et al. [52]. Of 756 coaches surveyed, a total of 136 "best practice" coaches were selected for the study based on affirmation of having used a training program (at any time) specifically aimed at ACL injury prevention. These coaches also had to incorporate at least three of five program elements such as feedback on technique, hamstring strengthening, cutting drills, balance training, and core stabilization. Only 19.8% of the 136 coaches were currently using an ACL injury prevention program. Factors that had significant associations with program usage were >7 yr. of coaching experience (odds ratio [OR], 2.69) and the presence of additional team staff such as an athletic trainer (OR, 2.57), a team physician (OR, 3.62), or a strength and conditioning coach (OR, 5.20). The coaches believed that, in order to be successful, ACL injury prevention programs should improve performance, additional coaching staff is required, and soccer organizations should enact policies requiring ACL prevention education and implementation.

Critical Points

- Coaches frequently responsible for development and implementation of training programs; qualifications and knowledge important in influencing injury risk.
- RE-AIM and RE-AIM SSM models successfully used in coach-implemented netball and soccer studies.
- Overall low percentages of coaches with existing knowledge of ACL injury prevention are using programs on a routine basis.

26.4 Knowledge and Attitudes of Athletes Toward Injury Prevention

Understanding motivation and compliance of athletes participating in ACL injury prevention training is crucial in the continual development and implementation of these programs. The attitudes and perspectives on female athletes' willingness to perform a lower extremity injury prevention program were studied by Martinez et al. [53]. The population included 76 high school soccer, field hockey, and volleyball players who all participated in a warm-up program for one entire athletic season. The athletes were encouraged to participate in the program that was supervised by a research assistant; however, coaches did not mandate training. The median attendance rate (no. of sessions attended divided by total number of sessions offered) was 69% (range, 11–95%). Athletes indicated they would be willing to participate in the program if data proved they would have fewer injury risk factors, be less likely to suffer an ACL injury, and be less likely to suffer leg injuries. Other motivational influences were other teams (including colleges and universities) and their favorite athletes participating in the program. Athletes with high attendance rates believed the program improved their overall health and quality of life. Interestingly, the athletes' beliefs and attitudes toward the program did not affect their attendance rates.

A study was conducted in 74 high school female basketball players (and 12 coaches) in the state of Massachusetts to determine their knowledge, attitudes, and beliefs regarding ACL injury risks and injury prevention programs [46]. The study participants answered questions regarding knowledge of anatomy, function, and ACL injury risk factors, attitudes and beliefs toward ACL injury risks and prevention, and their practices of ACL injury prevention techniques (Table 26.5). Then, an intervention program comprised of two strengthening, two jumping, and ten flexibility exercises was introduced and recommended to be performed during the 8-week season. Participation was voluntary and not tracked. At the end of the season, the athletes completed the questionnaire again (Table 26.6). Players of coaches who scored higher on the ACL knowledge scale had more favorable attitudes toward ACL injury prevention training (Table 26.7). Players who scored lowest on the knowledge and attitude scales came from a team whose coach also scored the lowest. The authors concluded that knowledge regarding the role of the ACL and injury prevention techniques are not well known, despite the influence of media on the topic.

Table 26.5 Sample questions from the knowledge, attitudes, and practices questionnaire [46]

Section	Questions
Knowledge	The role of the anterior cruciate ligament is to __?
	How often does a female high school athlete injure her ACL?
	At what point during a game is a player more likely to injure her ACL?
Attitude	I believe that landing from a jump shot on two feet will decrease my chances of injuring my ACL
	I believe that having strong thigh muscles will help protect my ACL
	I am concerned about injuring my ACL
Practice	I incorporate new techniques learned during practice in games
	I strength train my lower body at least twice a week
	I land on two feet with my knees bent from a jump during practice

Table 26.6 ACL knowledge, attitudes toward intervention training, and practice of intervention training in high school players [46]

Participants	Knowledge scale (mean points)	Attitude scale (mean points)	Practice scale (mean points)
Preseason (before intervention)	57.3	73.5	58.4
Postseason (after intervention)	61.8*	77.2	59.5

Scales, 0–100 points. Higher scores indicate greater knowledge, better attitudes toward ACL injury prevention training, and more frequent use of injury prevention training techniques

*$P < 0.01$ compared to preseason

Compliance with home-based injury prevention training was assessed in a study of 27 female high school basketball players [54]. Players were provided with exercise instruction and a DVD and were asked to perform the program three times a week for 8 weeks. Only 11% performed the program as instructed. Barriers to compliance were limited time and failure to remember to perform the exercises.

A study involving 408 players, 292 parents, and 73 coaches from Canadian soccer teams was conducted to determine their awareness of the risk of knee injuries and injury prevention programs [55]. Overall, 71% were aware of these injuries (Table 26.8). However, only 42% of players, 50% of parents, and 62% of coaches were aware that knee injuries could be prevented (Table 26.9). Those who were aware of prevention programs had varying responses regarding what activities were required for the program to be successful (Table 26.10). The investigators concluded that there were substantial gaps in knowledge regarding knee injury prevention programs and effective prevention strategies. This study identified, in this population, an urgent

Table 26.7 Changes in high school basketball players' knowledge, attitudes, and practices [46]

Scale	School #	Baseline score, mean pts	Change in score, mean pts
Knowledge	1	58.3	9
	2	53.2	10.1
	3	66	1.4
	4	49.3	−0.01
	5	59.4	1.25
Attitude	1	73.5	7
	2	69.8	5.4
	3	80.2	1.85
	4	68.2	−5.0
	5	73.8	7.5
Practice	1	60.9	5.1
	2	66.4	2
	3	54.3	0.5
	4	60.2	−1.6
	5	60.2	−0.4

Scale scores, 0–100 points

Table 26.8 Soccer players, parents, and coaches responses to “How often do you think sudden-onset knee injuries occur in females while playing soccer?” [55]

	Players (%)	Parents (%)	Coaches (%)
Never–rarely (<10%)	2	7	16
Sometimes (10–20%)	29	41	42
Often (20–50%)	38	33	26
Very often (>50%)	10	8	11
Don’t know	18	11	1
No response	3	1	3

Table 26.9 Soccer players, parents, and coaches responses to “Can knee injuries be prevented?” [55]

	Players (%)	Parents (%)	Coaches (%)
Yes	42	50	62
No	21	26	21
Don’t know	33	22	12
No response	5	2	6

Table 26.10 Soccer players, parents, and coaches responses to “Activities to prevent knee injuries (select all that apply)” [55]

	Players (%)	Parents (%)	Coaches (%)
Longer warm-up	59	70	73
Balance activities	28	49	49
Quadriceps strengthening	28	69	62
Increased fitness	35	66	76
Stretching	79	77	82
Biking	9	27	38
Jump training	17	34	40
Other	5	9	2

need for dissemination of knowledge of prevention programs and long-term consequences of serious knee injuries.

Critical Points

- Understanding athlete motivation factors crucial for program compliance and attendance.
- Knowledge and attitudes of coaches have a major impact on athlete acceptance of important of injury prevention training.
- Knowledge gap still exists among athletes, coaches, and parents regarding effectiveness of knee injury prevention training.

26.5 A Method for Certification and Education of Coaches and Trainers for ACL Intervention Programs

In order to provide coaches, trainers, and other health professionals with the scientific basis and justification for ACL injury prevention training, a formal education program was developed 15 years ago at our foundation. The 11-h course promotes the widespread dissemination of the scientific basis and accurate knowledge on the function of the ACL, injury mechanisms, the gender disparity in injury rates within various sports, risk factors, risk screening tests, neuromuscular retraining techniques, and sports-specific speed, agility, strength, and conditioning exercises and drills. The course comprises a blend of didactic lectures, practical demonstrations, and participant involvement and requires each participant to achieve a passing grade on a written and practical examination. The major components are based on specific objectives designed to provide the final goal of the participants able to implement local community intervention training. Some of these objectives include:

- Research background:
  - Understand injury/exposure rates.
  - Identify possible causal factors for increased risk of knee injuries.
  - Identify neuromuscular indices evaluated to measure training effects.
- Program training overview:
  - Understand different learning styles.
  - Identify neuromuscular deficiencies to be corrected.
  - Understand rationale for jump selection and progression.
  - Demonstrate at least two different styles of teaching/cueing.
- Implementation options:
  - Identify different target population for training options.

  - Identify ancillary and complementary methods to implement training.

The major topics of the didactic lectures include:

- Mechanisms of ACL injuries
- Gender differences in ACL injury rates, risk factors
- Neuromuscular training program development
- Scientific basis for program: studies demonstrating reduction ACL injury rate, improvement in athletic performance indices
- Strategies to improve neuromuscular deficiencies, reduce risk injury
- Instructions on neuromuscular, jump, speed, agility, and strength exercises
- Risk screening tests

One component of the education process is the requirement of the participants to perform each of the plyometric, strength, speed, agility, and flexibility exercises. This is done under the supervision of experienced faculty, who provide feedback and corrections. Then, the participants learn various methods and verbal cues to use to teach the exercises and drills to athletes in a manner which reduces the risk of an ACL injury to the best of the current knowledge.

Extensive written materials are provided to the participants, along with DVDs of the exercise components that contain step-by-step instructions. Software is included for the video drop-jump test. Some of the written materials include:

- Handouts for all didactic lectures
- Reprints of research studies supporting risk screening and neuromuscular retraining programs
- Step-by-step instructions for neuromuscular, jump, speed, agility, and strength exercises
- Recommendations for implementation of program: space, staff, equipment
- Recommendations for use of the program for patients who have had an ACL injury, reconstruction
- Training logs
- Marketing information, approaches to use in implementation of the program

To date, over 2700 trainers have attended this course from the United States and abroad including Austria, Brazil, Canada, Finland, Iceland, the United Kingdom, Japan, Qatar, The Netherlands, and Singapore. We believe that some of the problems identified in this chapter in regard to coaches' knowledge, attitudes, and beliefs will be lessened from this type of formal program. It is apparent that the knowledge and attitude of the personnel who conduct ACL intervention training are quite influential for the success or failure of the program.

26.6 Conclusions and Recommendations

The widespread implementation of ACL injury prevention programs requires efforts at multiple levels and includes many disciplines. The following requirements are identified as important areas to achieve success:

- Disseminate and integrate information on ACL intervention programs to those directly involved with athletes such as school coaches, physical education teachers, athletic trainers, league coaches, strength and conditioning specialists, school administrators, primary care physicians, and pediatricians. Include the entire tier of sports hierarchy, from local clubs and schools to national sports organizations. Use a formal course format, including lectures and participant involvement, demonstrating understanding of correct teaching techniques for training principles.
- Target governing bodies of sports organizations in order to facilitate or regulate the integration of ACL injury prevention training principles into routine team practices.
- Request financing assistance from major sports organizations (National Collegiate Athletic Association, National Basketball Association, Women's National Basketball Association, National Soccer Association,

National Football League Charities), sports industry for-profit companies (Adidas, Nike, Reebok), sports medicine organizations (National Athletic Trainers' Association; American Academy of Orthopaedic Surgeons; American Orthopaedic Society for Sports Medicine; International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine; American College of Sports Medicine), orthopedic and sports medicine research organizations (National Institutes of Health, Orthopaedic Research and Education Foundation), and individual philanthropists.

- Target insurance and hospital organizations to participate in local prevention programs to decrease knee injuries in the community they serve.
- Continue to study risk factors and develop high-risk biomechanical profile using findings from collaborative multisite studies. Develop screening procedures that can be done during routine pre-participation physical examinations.
- Use appropriate public health models such as RE-AIM to study outcome, implementation, and feasibility of ACL intervention programs.
- Use intervention methods as detailed in Chap. 27.

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Implementation Strategies for ACL Injury Prevention Programs

27

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Abstract

There is a critical gap between research-based evidence supporting the use of neuromuscular training programs for ACL injury prevention and real-world effectiveness due to limitations in disseminating and implementing these programs. This chapter presents an integrated approach addressing topics from public health and behavior change literature with the knowledge base of ACL injury prevention. A pragmatic framework that incorporates common barriers and facilitators is discussed along with ideas for solutions to help the clinical and/or sport coach or administrator facilitate implementing these efficacious interventions.

27.1 Introduction

ACL injury prevention efforts have focused on either reducing injury risk or improving movement control through a multifaceted exercise-based preventive training program. A combination of balance, strengthening, agility, flexibility, and plyometric exercises while emphasizing proper movement control is a critical element of an effective program. Movement control can be encouraged by providing specific cues and feedback to athletes, such as "land softly," "keep your knees over your toes," and "bend your knees" to emphasize proper force absorption and optimal alignment. Preventive training programs frequently require 10–20 min to perform and have reduced the risk of ACL injuries [1–4], other internal knee derangements [2, 3, 5], and all lower extremity injuries [6, 7]. Preventive training programs are also effective with improving movement control [8, 9], reducing knee valgus [10–13] and vertical ground reaction forces [14–16], as well as increasing knee flexion [10, 11, 17]. Despite these documented benefits of preventive training programs, program adoption is not widespread in sport.

Less than 20% of adolescent female sport coaches report implementing a preventive training program with their teams [18–20]. This low percentage does not seem to be related to a lack of awareness about preventive training programs or knowledge of ACL injuries [20]. Frank et al.

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[21] performed a study investigating the effect of a coaches' workshop on ACL injury prevention in youth soccer. Even though coaches reported comfort with implementing a program and demonstrated knowledge about the program, only 53% actually implemented the program during the subsequent season with varying fidelity. Coaches that do choose to implement programs often compromise program fidelity by removing some of the included exercises, which can compromise the benefits of a program [5, 22].

High compliance with preventive training programs is critical for injury prevention [2]. Sugimoto et al. [23] reported in a meta-analysis that total exposure to a preventive training program was directly related to injury rate reduction. Hagglund et al. [24] observed an 88% reduction in ACL injuries among female adolescent athletes that completed the program with high compliance compared with no difference between athletes completing a control program or had low compliance with the preventive training program. Similarly, Steffen et al. [25] also demonstrated a protective effect, as measured by reduced injuries and improved balance, in athletes who completed the preventive training program with high adherence to the program design compared with all other athletes. Therefore, there is a critical need to promote the initial adoption of preventive training programs, as well as ensure long-term sustainability and fidelity in order for widespread ACL injury prevention.

27.2 What Is Implementation?

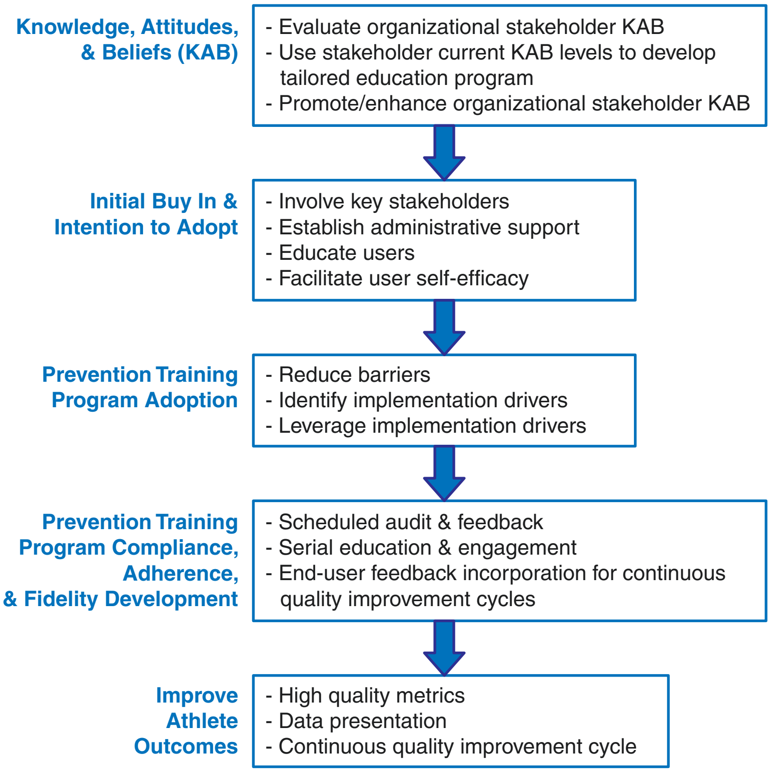
In order to experience and retain positive training results, preventive training programs (PTPs) must be adopted with high compliance, fidelity, and maintenance. Operationally, compliance indicates that a PTP was executed in general and positively answers the question, "Was a program completed?," whereas fidelity refers to the quality of the performance and if the exercises were performed correctly or as instructed [26, 27]. Maintenance describes the continued PTP behavior; does the team or player use the PTP regularly across time [27]? In general, the PTP implementation process begins with (Step 1) a coach or team possessing the appropriate knowledge, attitudes, and behaviors to buy in and intend to adopt a PTP. This leads to (Step 2) initial adoption of a PTP, which if continued over a period of time would develop characteristics of (Step 3) compliance, fidelity, and maintenance with PTPs. Ultimately, compliance, fidelity, and maintenance contribute to program dosage, which is a measure of how much exposure an individual athlete experiences to a PTP. There are multiple components impacting this measure, including duration of individual session, number of times the PTP is performed in a given week, number of weeks in a given season, etc. Research has indicated that increased PTP dosage can improve retention of neuromuscular outcomes [28]. With that, Step 3 components that impact dosage leads to Step 4, athlete outcomes in which the goal of PTP usage is to reduce injury risk and injury rate long term (Fig. 27.1).

27.3 Theories of Implementation

There are a plethora of intervention implementation frameworks that have been used by the field of health behavior change and implementation science. One framework promoted for use by the sports medicine community is the Reach, Effectiveness, Adoption, Implementation, Maintenance (RE-AIM) framework, which accounts for the reach of the intervention through the maintenance of the intervention over time [29]. O'Brien et al. [30] performed a systematic review to evaluate if and how aspects of this framework have been addressed in preventive training program dissemination and implementation. Their conclusions highlighted significant gaps in adoption and maintenance regarding preventive training programs.

To examine barriers and facilitators to health behavior change, the Theory of Planned Behavior is composed of three main constructs: attitudes, subjective norms, and perceived behavioral control that are reasoned to impact a person's intention and subsequent control over a specific behavior. Frank et al. [21] recently used the

Fig. 27.1 Preventive training program implemenation steps



Theory of Planned Behavior in conjunction with Reach, Effectiveness, Adoption, Implementation, Maintenance in a Sports Setting Matrix (RE-AIM SSM) to determine the impact of a coach's workshop on behavioral determinants and initial adoption of PTPs. This study determined that the preseason workshop improved behavioral determinants, but those improved determinants did not translate into initial adoption of PTPs. Future research is needed to uncover what barriers and behavior drivers motivate PTP implementation. The results of Frank et al.'s study [21] implicate that intent to implement alone may not facilitate successful adoption of a PTP. Thus, it is important to integrate implementation drivers [31] to leverage a stakeholder's intent to carry out their intended actions to execute their specific planned behaviors.

While researcher-led PTPs have increased the efficacy knowledge base, implementation research occurs in a real-world context and health behavior strategies need to be employed in order to account for the variation in human behavior and environment. Over the last decade, few studies outlined appropriate methods for effective real-world dissemination [32, 33]. Finch et al. [34] specifically identified the Translating Research into Injury Prevention Practice (TRIPP) framework as a good model to describe injury prevention studies, where Stages 5 and 6 are of particular importance for widespread diffusion and application to different populations.

Stage 5 calls for a thorough description of the context of a given study so that the methodology can be more accurately applied to other populations. Stage 6 is an evaluation of a PTP's effectiveness within the given setting of a study. Padua et al. [35] built on this framework by providing seven steps to further operationalize the development and implementation of PTPs within the TRIPP framework. This expansion is a stepwise approach that identifies the population, compromises an effective PTP, and ultimately leaves the population autonomous. Together, these two guides provide a way to systematically understand barriers and facilitators to health behavior within the context of PTP effectiveness. However, despite efficacious, evidence-based programs and roadmaps for implementation, PTPs are not always successful.

Despite progress in reporting and describing evidence-based PTPs [21, 36], implementation sometimes fails [37]. While many social cognition and health behavior change theories exist, the layers and complexities involved with widespread implementation can be challenging; what is effective in one population may be unrealistic or ineffective in a different setting. In order to best elucidate why implementation may fail, we need to broaden the TRIPP framework identified above to a more generic approach. Intervention mapping broadly outlines the process [38] (Table 27.1).

When viewing the intervention mapping technique as a cascade of events, it is easier to see where breakdowns in the process may occur and impede successful attitude and behavior change. The focus of PTP research has been on the implementation process with respect to Steps 1, 2, 5, and 6. This body of evidence has helped to clearly support that there is a direct relationship between PTP dosage and long-term injury risk reduction, indicating a need for athletes to continuously use PTPs with high fidelity over the long term [7, 39].

Table 27.1 Intervention mapping

Step	Step description	Relevant theories
1	Needs assessment	Socio-ecological approaches to (a) the problem and (b) the solution
2	Choose approach	Social cognition models: Theory of Reasoned Action, Theory of Planned Behavior, Health Belief Model, Protection Motivation Model
3	Plan feasibility	
4	Plan, revise, produce program materials	The PTP Training materials/ techniques
5	Plan adoption, implementation, and maintenance	RE-AIM, context-specific community diffusion
6	Plan evaluation	Process, outcomes, etc.

PRP prevention training program, *RE-AIM* reach, effectiveness, adoption, implementation, maintenance

In conclusion, there are numerous theories, models, frameworks, and strategies to approach education and PTP dissemination. The last 10 years of PTP implementation research has surged in delineating frameworks and describing the steps taken toward implementation. This same effort needs to be put toward specifically describing educational techniques and strategies to promote coach education efforts and long-term behavior adoption.

27.4 Pragmatic Framework to Improve Implementation

One systematic framework created to guide the development and implementation of evidence-based preventive training programs is Padua's seven steps. This framework is particularly useful because it accounts for the unique environments of sport, military, or other settings where PTPs might be used. Each step, outlined below, guides users through the process and helps to operationalize tasks in order to improve implementation efforts.

27.4.1 Step 1: Establish Administrative Support

Gaining administrative support prior to beginning preventive training program implementation is a critical element for the success of preventive training programs. Although “bottom-up” approaches, or initiatives developed and driven by community members themselves, can successfully facilitate change, “top-down” approaches, or field expert-driven interventions, may simultaneously maximize efforts. Administrators and leaders often control assets and resources, which may limit the initial stages of program implementation if these individuals are not committed. Only three published preventive training program studies [4, 40, 41] have even included this first step of implementation, which may help to explain the poor compliance frequently observed in the literature. Gaining “permission to implement” at the very beginning will likely facilitate long-term sustainability of the program, which is a poorly reported or discussed aspect of preventive training program implementation. Engaging with these individuals in the planning process will help ensure implementation addresses barriers and facilitators specific to each organization.

27.4.1.1 Keys to Achieving Support

Administrators such as athletic directors, presidents, and principals are more likely to implement or support a preventive training program if it is aligned with how the overall organization is evaluated for success. For example, the success of most sports teams is usually based on win-loss percentages. Demonstrating to these administrators with specific data regarding how a preventive training program can directly improve winning percentages by reducing time lost form injuries may be a vital element for gaining acceptance. In the military, key outcomes to demonstrate to these administrators is the simultaneous benefit to physical fitness and stress resiliency outcomes, such as the Army Physical Fitness Test [42].

Specific discussion points for administrators frequently include the following: (1) address the negative outcomes of injury and how these negative outcomes directly hinder the organization's goals, (2) proactively demonstrate how a preventive training program will not detract from focus and attention on the organizational goals but actually facilitate these objectives by keeping athletes participating at their peak performance, and (3) address the concept of "relative advantage," perceived efficiencies or benefits of the PTP over current practice or strategies [43].

27.4.1.2 Common Barriers Encountered

A common barrier to gaining administrative support, as well as "buy-in" at subsequent stages of implementation, is the perception that the organization's current policies, such as a dynamic warm-up that is already sufficient for injury prevention. Efforts to overcome this barrier should focus on demonstrating why the evidence-based preventive training program has a relative advantage over current practices. However, this barrier can also be used to facilitate efficient change if the organization is indeed already committed to a type of dynamic warm-up, which may be a barrier in itself with some organizations that do not perceive any benefit from a structured activity prior to sport. In contrast, using their existing practices or warm-up as a framework for simple revisions to make the program evidence-based may enhance the implementation process and overcome common challenges.

For example, a high school girls' basketball team already performs a 10-min dynamic warm-up program that consists of dynamic flexibility, strengthening, and agility exercises. Discussions with administrative personnel, as well as other stakeholders, should demonstrate strengths of the existing program (e.g., consistently performed dynamic warm-up, including flexibility, strengthening, agility exercises) and areas where the program fails to be evidence-based to improve lower extremity neuromuscular control (e.g., include balance and plyometric exercise with quality movement instruction and feedback).

27.4.2 Step 2: Develop an Interdisciplinary Implementation Team

An interdisciplinary team for preventive training program dissemination and implementation can improve long-term feasibility and maintenance (Table 27.2). Stakeholder involvement from all organizational levels, including the program implementers (those involved in program development and daily operations), program supporters (e.g., parents, administrators), participants (those served or affected by the program), and decision-makers (those that can influence program use and support), can help avoid logistical barriers for long-term implementation [24, 29, 35, 44]. Involving potential critics or adversaries of the program may also be beneficial to address implementation barriers up front. Published interventions have primarily focused on only involving coaches and athletes. This may greatly limit long-term maintenance and sustainability as the general "one size fits all" implementation

Table 27.2 Stakeholder examples

Stakeholder	Definition	Example of personnel
Program implementers	Those involved in program development and daily operations	Director of coaching, coaches
Program supporters	Those who approve and encourage the implementation of the PTP	Parents, organization administrators, coaches
Participants	Those served or affected by the program	Athletes
Decision-makers	Those that can influence program use and support	Organization administrators, coaching directors, coaches

approach does not account for individual organizational needs or address stakeholders' perceptions of which stakeholders should be involved in the process. For example, parents may be a critical voice to promote the initial adoption of a preventive training program so ensuring parents have an opportunity to learn and share their opinion is beneficial. Parents may also have a perception that the team physician, when applicable, should be involved in implementation. Including the team physician may encourage buy-in from the parents, as well as provide another stakeholder that can promote the need for the program to improve immediate injury rates, as well as long-term health. Failing to secure input from important organizational stakeholders may inhibit program adoption and/or long-term maintenance across the organization.

27.4.3 Step 3: Identify Barriers and Solutions

Implementation barriers can frequently be grouped into four primary categories: time, environment, personnel, and organization. Specific barriers within each category will likely differ between organizations, but the general categories can be used to quickly identify the organization-specific implementation barriers. Once these barriers are identified, a scalable program can be developed to address the barriers and ensure the program remains evidence-based for injury prevention.

27.4.3.1 Time

Time is one of the most commonly reported barriers encountered with preventive training program dissemination and implementation [20]. Time can include the following aspects: time of day for program implementation, duration of each program implementation session, frequency of program implementation each week, and number of weeks devoted to programming.

Preventive training programs can be implemented as focused individual or team training sessions or incorporated into existing team sport practices. The majority of the published studies on preventive training programs have used the dynamic warm-up opportunity for program implementation. These warm-up programs typically require 15–20 min of training. Longer programs requiring more than 60 min likely improve neuromuscular control faster and may promote gains in muscular strength and power [45]. Sugimoto et al. [23] demonstrated that program dosage is directly related to program effectiveness. Most programs are designed to be completed throughout a season but also can be implemented with more frequent and/or longer program dosage during preseason and subsequently shorter and less frequent implementation after preseason concludes [46].

Longer duration programs per session may not meet the needs and expectations of every setting. Time to complete may be one possible explanation for poor compliance with existing preventive training program published studies. Martinez et al. [19] surveyed youth basketball and soccer coaches regarding their willingness to perform a preventive training program that required 5, 10, 15, 20, or 30 min of practice time. The authors reported that over 80% of coaches were willing to perform a 10-min program or less, but fewer than 50% of coaches were willing to implement a program that required 15 min or more. The time to complete previously published preventive training programs per day may need to be reduced in order to gain coach compliance.

A common question regarding program implementation is if one season of exposure is sufficient for long-term benefits. Several studies indicate that interventions less than 3 months in duration do not result in permanent retention of neuromuscular outcomes [28, 47]. These findings suggest that true learning of new movement has not occurred. In order to maximize total exposure to the program and long-term protection, preventive training programs likely need to be performed on a regular basis throughout a season and every season. Educating stakeholders that preventive training programs need to be implemented regularly similarly to sport-specific skill training, such as practicing foul shots or foot skills, is imperative.

In addition to improving long-term injury prevention, performing preventive training programs on a regular basis may result in habit formation. This may be particularly important for young athletes who are just learning the “normal” routines of sport participation. Introducing preventive training programs to these young athletes as a regular aspect of sport participation, and the social norm, may greatly improve long-term attitudes and intention, which are critical for the adoption of any health behavior [48]. Improving neuromuscular control through preventive training programs in children during critical periods of motor development prior to age 13 is also likely critical to maximize injury risk reduction when they reach adolescence, which is when injury risk is greatest. Furthermore, regular practice of the preventive training program likely yields improvements in an individual athlete’s self-efficacy, or belief in one’s ability to successfully perform the program and participate in sport [49].

27.4.3.2 Environment

Potential barriers to preventive training program implementation related to the environment include equipment and space to train. Fortunately, most of the evidence related to the positive effectiveness of preventive training programs has been found with programs that did not require any equipment. Most programs are implemented as a warm-up prior to sport participation and therefore, performed on location for that activity. Heidt et al. [50] and Hewett et al. [51] are the only two studies that were not performed as a team warm-up activity and consequently performed at a location other than the sport setting with success. Implementing the program on location of the sport setting likely overcomes the potential barrier of environment. There may be some situations where space is limited, such as during basketball where the team wishes to perform the warm-up before courts are available, in military, or other large-scale settings. In these cases, programs can be modified to be performed in formations, such as a football warm-up grid or military formation positions, to protect valuable space depending on the requirements of the implementation context [52].

27.4.3.3 Organization

Organizational concerns are major barriers to overcome in order for an intervention to be sustainable over time. As discussed previously, communicating with an organization about the relative advantage of the preventive training program over their current practices is one major focus of efforts to address organizational concerns. An organization, such as a sports team, may also be concerned about the acute and long-term benefits, or harm, to the individuals or athletes.

Current published evidence regarding preventive training programs has understandably tested the effectiveness of a standard intervention program without individual organization modifications. While this strategy is beneficial for understanding the effect of the programs, it likely does not represent best practice for disseminating and implementing a program in the real world. For example, coaches often express concern that the preventive training program may result in fatigue that hinders their performance during the subsequent competition or training session. Fortunately, there is no evidence that dynamic warm-ups of any kind causes any harm to common measures of sport performance, including vertical jump, sprint speed, and agility time [11, 53, 54]. Further, one session of performing a preventive training program can facilitate improvements in movement control. Although this improvement is likely transient until permanent motor learning occurs, the improvement may improve movement efficiency and encourage appropriate joint loading during the subsequent training session. Performing preventive training programs as a sport warm-up presents an effective method of preparing athletes for competition and a regular time to incorporate these efforts into training.

Time to perform the preventive training program is always a concern for organizations. Implementing the program as a team warm-up presents a natural opportunity to expose the program to all athletes, or individuals, in most settings. However, in some specific situations, it may be beneficial to screen athletes for high risk and target those individuals, specifically. The most significant risk factor for ACL injury is a prior injury; therefore, any individual with a history of an ACL injury should be completing a preventive training program with high compliance and fidelity. Gilchrist et al. [55] demonstrated that these individuals may have the greatest protective benefit from these programs.

There are several clinical movement screens available that organizations can use to identify individuals with the greatest room to improve. Once the population of athletes is screened, those with poor control can be identified and assigned specific preventive training programs. Customizing preventive training programs for specific movement compensations may also improve program efficiency. While performing personalized screening and preventive training prescription may be more efficient for individual athletes to address his or her specific risk factors and devote more time to those exercises, this may not be realistic for large teams. Furthermore, it may be challenging for athletes on a team to perform different preventive training programs compared with other athletes. In these situations, a general “one size fits all,” or comprehensive, program that is disseminated to the entire team and addresses many potential risk factors may have the greatest potential and be more feasible for teams to comply with and perform regularly.

27.4.3.4 Personnel

The personnel needed to implement the preventive training program is a critical consideration. In most settings, the coach or team leader, such as a captain, can serve this role, and this model has been used in most research regarding preventive training program effectiveness. However, a primary barrier to effective coach implementation is the coaches’ perceived self-efficacy. Providing coaches with the knowledge, tools, and confidence to implement the programs are imperative. Pryor et al. [56] demonstrated that a 90-min coaches’ workshop can effectively result in high program compliance and be effective with improvement movement control in youth athletes.

Frank et al. [21] reported that coaches’ workshops can also improve coach perceptions and self-efficacy to incorporate an injury prevention program in to their training sessions. However, it is important to note that these authors did not observe increases in self-efficacy and perceptions to translate to increased adoption and fidelity of injury prevention program. Thus, it is important to engage other organizational stakeholders in the implementation programming rollout. Key stakeholders include athletic trainers, strength and conditioning professionals, organizational administrators, parents, and end users such as the athletes themselves. A comprehensive approach to engage and implement a successful injury prevention program will facilitate stakeholder implementation synergy, which has been indicated to enhance programming success [57, 58].

27.4.4 Step 4: Develop an Evidence-Based Preventive Training Program

After the barriers and facilitators for preventive training program implementation have been identified, the actual program can be designed. The F11+ preventive training program is the most commonly studied program among published evidence [25, 59, 60]. However, program effectiveness has been established from other preventive training programs, with meta-analyses [61–63] demonstrating that there is no single program responsible for positive effects, but rather specific components are required. Specific components include using a combination of strengthening, flexibility, agility, plyometric, and balance exercises while incorporating high-quality movement instruction and feedback. For example, some organizations may desire the program to include sport-specific exercises. Program exercises also need to match the ability levels of the athletes involved with the program so progressions and regressions of each exercise should be considered. The ability to modify a program to meet the needs of a specific organization is invaluable for a program's sustainability over time.

27.4.5 Step 5: Train the Trainers and Users

As discussed previously, educating and preparing the individuals with primary responsibility for actual program implementation is essential to facilitate adoption, fidelity, and maintenance.

Two studies simply supplied program implementers (i.e., coaches) with educational materials via web-based platforms or mail [51, 60]. Six studies (50%) supplemented the educational materials with an in-person training workshop [1, 4, 5, 25, 41, 59, 60, 64]. Kiani et al. [46] offered an in-person workshop upon request, but did not describe how often this type of training was used.

Steffen et al. [25] compared the effectiveness of three different training strategies for program implementation. The control group received access to web-based materials while the intervention group coaches attended an educational workshop. One intervention group of coaches also received supplemental implementation support from a trained health-care professional weekly throughout the season. Interestingly, there was no difference between the two intervention groups, suggesting an educational workshop can be an effective method to train coaches to implement a preventive training program.

However, in order to facilitate long-term PTP compliance and maintenance, coaches must be empowered to conduct PTPs autonomously. In community level youth sports, coaches have a spectrum of experiences and injury prevention knowledge, frequently resulting in inadequate PTP compliance [20].

27.4.5.1 Selecting Content: Targeted Versus Tailored Approaches

One method to ensure that coaches' training includes relevant behavior change determinants is to use a tailored education approach. Previous approaches to coach education have been targeted in nature, focusing on general behavior determinants found to be relevant for a coaching population. However, coach populations can vary tremendously, from coaching experience, whether the coach is a parent, the age and competition level the person is coaching, the gender the person is coaching, etc. All of these factors can contribute to a variety of information interests.

Conversely, a tailored approach takes the specific population of coaches being trained (for instance, a single soccer league), conducts a needs assessment to determine which information would be most motivating for each person, and then designs the educational training based on the assessment findings [65]. While this may seem unrealistic for widespread dissemination, growth in automated algorithms and technology may help to streamline this process in the future. This approach has been successfully used in health and wellness strategies, as well as in medical school curriculum [65, 66].

27.4.5.2 Application of Educational Techniques from Other Fields

Discourse

Discourse, or communication language between a teacher and student or student with another student, helps learners apply content into practice [67]. PTP implementation has been closely linked to program fidelity and frequently emphasizes the need for continuous feedback on exercise form [9, 22]. During training, it may be important to encourage participant communication and to make training as interactive as possible while limiting didactic lecture [68]. This type of strategy should increase the learners' time spent on task and help the person to engage with the material more deeply, which in turn may improve the learners' self-efficacy and confidence with implementing PTPs independently in the future [69–71].

Social Cognitive Theory

The Social Cognitive Theory is an expansion of the social learning theory, where a learner is able to learn a behavior based on a combination of observations of the behavior and an understanding of the positive and negative consequences of the behavior [72]. With observational learning, a coach watches a researcher or educator set up and run a PTP. The next step is active learning, where the coach engages in hands-on learning and works to implement the PTP in a contrived scenario with other coaches in the workshop. In combination with discourse, the coach is able to first learn (discourse), then see (SLT observation), and then do (active learning). If followed by a debrief session to address questions and to ensure positive and negative consequences of the behavior are reiterated, this learning sequence may promote an effective long-term learning experience.

Mentorship

One aspect of coach learning that has been studied at a cross-sectional level in PTP implementation is the impact of role-modeling from other coaches and administrative support [73]. In this respect, coaches stated they would be more likely to engage in PTP use if he or she felt that other coaches that he or she considered experts in the field were also using PTPs. To create this social network and social norm, researcher-led mentorship may need to be established for a period of time. Researchers could connect similar leagues to each other to build a social network, or serve as a continued resource for advice and troubleshooting help.

Adult Learning

Other components to keep in mind during education strategizing are the differences between adult and child learners. Adult learning, or andragogy, may consider that adults tend to be more self-directed and incorporate life experiences and knowledge into learning [74]. This is particularly relevant for coaching education, where experience with specific sports, both playing and coaching, will heavily influence a coach's willingness and ability to implement a PTP. Incorporation of previous knowledge and experience can actually be a strength of coaching education, where coaches can take ownership of their team warm-up while still learning important injury prevention techniques.

Few studies have clearly described educational components to use during workshops [21, 25, 73, 75–77], and even fewer have followed up to ensure that the coaches demonstrate the behavior [21, 25]. There is a need to better understand approaches to PTP education in order to reach a variety of coach audiences and to promote attitude and behavior change.

27.4.5.3 Educational Techniques to Stimulate Learning Determinants of Behavior: Knowledge, Attitudes, and Behavior

While evidence-based researcher-led PTPs have been identified [7, 9, 53, 64, 78], there is limited information regarding appropriate curricula and education techniques for workshops [21, 35, 36].

Initial research into this area has looked at determinants of stakeholder behavior through analysis of knowledge, attitudes, and behaviors [18, 20, 21, 73, 77, 79, 80]. Unfortunately, although preseason education training sessions have been shown to increase knowledge, attitudes, and intention to adopt PTPs [21, 25, 75], intention to adopt a PTP does not necessarily predicate actual behavior change [21]. However, what have been studied thus far are determinants of behavior, such as knowledge and attitudes, and these components are not necessarily the same as determinants of behavior change [38]. Studies investigating coach behavior determinants have called for more exploration of behavior change determinants, such as top-down policy, perceived value, perceived self-efficacy, etc. [21, 76].

27.4.5.4 Content of Education

Padua et al. [35] identified pertinent topics of discussion to review during a train-the-trainers session for the US Military Academy. Over the course of a 2-h educational workshop, this study prioritized:

- PTP effectiveness
- Alignment with organizational supports
- Knowledge
- Self-efficacy
- Feedback

The effectiveness component focused on the positives of PTP use, such as injury reduction and improved athletic performance. During the training sessions, the research group was able to thoroughly describe each exercise and conduct hands-on training for implementation. While this is a good explanation of a training session, this particular study was afforded 2 h of the trainees' attention. Conversely, Frank et al. [21] sought to implement a PTP in a youth soccer league and was given 30 min to train the coaches. Frank et al. [21] emphasized PTP effectiveness in reducing injury and improving sport performance as well as describing individual exercises but had a much shorter amount of time available. Both studies also directed the attendees to supplemental materials online for further reference following the workshop.

The difference in time allotment between these two studies may be a common problem across implementation studies. There is a need to define specific strategies to use when brevity and succinctness are necessary.

27.4.6 Step 6: Fidelity Control

Fidelity is vitally important for the effectiveness of a PTP. The majority of studies have evaluated program efficacy in a controlled environment. High levels of implementation fidelity ensure incorporation of key components of PTP that are identified to promote effectiveness. Furthermore, previous work has illustrated that there is a propensity for low-fidelity implementation to actually result in poor outcomes [52]. Data suggest that when individuals are given materials and left to implement programming without regular fidelity feedback, the PTP may indeed increase an individual's risk of injury. Thus, it is imperative that an appropriate level of fidelity is maintained when implementing a PTP in a real-world context. Future research must explore the use of a fidelity feedback schedule that ensures long-term maintenance of the intended PTP.

27.4.7 Step 7: Maintenance and Exit Strategy

Currently, there are no published data that describe the long-term effectiveness of PTPs. Myklebust et al. [44] presented promising reductions in ACL injuries through the use of preventive training programs in Norwegian handball during a research study. However, these injury rate reductions were not permanent, because injury rates returned to the previous levels once the research study was complete. Norway was subsequently able to launch a national information and education initiative regarding preventive training programs, which resulted in a successful decrease in injury rates for at least 6 years. The Norwegian experience suggests further work is needed to promote preventive training program dissemination and implementation in a manner that will be sustained over time.

Conclusion

In conclusion, while prevention of ACL injuries appears possible, there is great need for all stakeholders involved in sport to be committed to preventive training program implementation. Common barriers to implementation in sport, such as time, personnel, and equipment, can be overcome through creative program design that maintains the fidelity of successful programs (integrated program including balance, flexibility, agility, plyometric, and strengthening exercises with an emphasis on appropriate movement control) and discussions with stakeholders about program delivery options. Following a pragmatic approach, such as the seven steps outlined in Padua et al. [35], may empower sport organizations to implement effective programing to yield long-term benefits and sustainability.

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28 Current Understandings and Directions for Future Research

Sandra J. Shultz and Randy J. Schmitz

Abstract

This chapter summarizes the findings and discussion focused on ACL risk factors, screening, and injury prevention from the 2015 ACL Research Retreat. Risk factors include neuromuscular, anatomical, structural, genetic, and hormonal. For each risk factor, the current understandings, key unknowns, and directions for future research are described. In addition, risk factor screening and injury prevention are discussed in a similar manner. A consensus statement was devised that reflects the most recent advances in this field.

28.1 Introduction

There is current consensus that multiple factors acting both in isolation and combination can contribute to noncontact ACL injury. Although advances in understanding these factors continue, there are remaining questions that need to be addressed to advance the field to ultimately prevent this devastating injury. In 2001, the ACL Research Retreat was cofounded by Irene Davis PhD, PT, and Mary Lloyd Ireland, MD, to present and discuss the most recent research on ACL injury risk and prevention and to identify new research directives aimed at understanding the epidemiology, risk factors, and prevention of noncontact ACL injury [1]. Subsequent retreats have been held in 2003 [2], 2006 [3], 2008 [4], 2010 [5], and 2012 [6]. The meeting typically features keynote presentations from expert scientists engaged in cutting-edge research and podium/poster presentations organized into thematic sessions with a focus on risk factor assessment, injury mechanisms, risk factor screening, and injury prevention. This meeting reserves significant time for group discussion and consensus building. At the first retreat in 2001, a consensus document was developed as to (1) what we know, (2) what remains unknown, and (3) what important directions for future research are needed to address these unknowns [1]. This consensus documented has been revisited and updated each retreat based on new evidence emerging in the literature and as presented at the retreat.

This chapter reflects content from the 7th ACL Research Retreat held in Greensboro, NC, USA, on March 19–21, 2015, that was originally published by the *Journal of Athletic Training* [7]. Clinicians and researchers from the United States, Australia, Canada, India, Ireland, South Africa, the Netherlands, and the United Kingdom

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participated in presentations and discussions divided into areas of (1) risk factor assessment, (2) screening, and (3) injury prevention. The consensus surrounding each of the areas as determined from the meeting is summarized here relative to current understanding and remaining questions designed to direct future research. Following these specific sections, some global observations, themes, and recommendations that emerged from the meeting are also included.

28.2 Risk Factor Assessment

28.2.1 Neuromechanical Risk Factors

Neuromuscular and biomechanical (neuromechanical) factors are considered to be those factors obtained during instrumented, biomechanical analyses of human motion. Such measures as joint motion, joint loads, and magnitude and timing of muscle activation are commonly investigated relative to ACL injury as they are thought to be most modifiable through training. Current understandings of ACL strain, movement biomechanics, and neuromuscular/neurocognitive insufficiencies are addressed here.

28.2.1.1 Current Understanding

Advances in understanding how the ACL is loaded and how ligament failure occurs have arisen from cadaveric and computer modeling of simulated knee loads. These studies have been instrumental in better understanding and interpreting "high-risk" movement biomechanics that do not estimate ACL loads or use ACL injury as an outcome. The ACL is loaded in vitro through a variety of isolated and combined mechanisms assumed to be present during dynamic sport postures considered to be high risk. Collectively, this work demonstrates that ACL strain increases during anteriorly directed tibial forces, tibiofemoral compression, and/or combined knee abduction and knee internal rotation moments [8–16]. Mechanical coupling of external moments about the knee that include internal rotation and abduction is in combination reported to increase ACL strains to near reported levels for tissue rupture [15].

Cadaveric work has applied knee loads designed to simulate activities representing high-risk ACL injury biomechanics. The timing of peak ACL strain is dependent on anteriorly directed tibial forces and knee abduction moments with peak internal tibial rotation occurring much later in the simulated landing [10]. In addition, knee abduction combined with internal knee rotation, anterior tibial translation, and increased tibiofemoral compression produces ACL injuries in cadavers that appear consistent with clinical observations of ACL injuries [17]. During simulated single-leg landing, peak ACL strain increases with a combination of higher ground reaction forces and decreased hip angles (more erect posture) [18]. Collectively, these cadaveric studies have clarified how the ACL is loaded and injured and provide the foundation for assessing variables thought to present "high-risk" movement biomechanics occurring in vivo during physical activity.

Females are commonly understood to be at greater risk of ACL injury than males, resulting in predominantly gender difference-focused investigations. Recent reviews have reported that females demonstrate greater knee abduction postures during landing [19, 20]. Given the prospective findings of Hewett et al. [21], knee abduction may be one factor in defining female-specific ACL injury mechanisms [20].

Noncontact ACL injuries are commonly reported to arise from a sudden deceleration during changing direction when running and/or landing from a jump [22]. Quantitative analyses of injury events demonstrate rapid knee abduction, and internal rotation occurs at the time of injury [23, 24]. Additionally, video observations of ACL injury occurrences report a relatively extended knee [25], greater knee abduction motion [26–28], increased amounts of lateral trunk motion [29], and more posteriorly positioned center of mass [30]. These observational findings are largely supported by the cadaveric investigations discussed earlier and provide support of studying high-risk biomechanical measures as outcome variables.

Limited work has demonstrated landing biomechanics to be prospective risk factors of ACL injury. Larger peak knee abduction moments and peak knee abduction angles at initial contact during a drop jump using three-dimensional biomechanical modeling may have a relationship to ACL injury in adolescent female athletes [21]. A study that used a more clinically accessible video observation of a jump-land (Landing Error Scoring System [LESS]) in youth soccer athletes reported that participants who went on to suffer an ACL tear had lower LESS test scores [31]. However, the LESS has not been demonstrated to be a predictor of ACL injury in high school- and college-aged athletes [32]. Thus, limited evidence exists to support that knee movement biomechanics can prospectively predict ACL injury.

An upright posture characterized by a more extended joint position is commonly associated with increased vertical ground reaction forces [33, 34]. This posture is important to understand because in vivo and in vitro studies indicate that ACL strain is related to ground reaction forces [35, 36]. Similarly, anterior tibial translations have been demonstrated to increase as demands on the quadriceps increase [37, 38]. Thus, this upright/extended posture when contacting the ground during the early stages of deceleration tasks has been suggested to be associated with the ACL injury mechanism [39–43]. Exertional protocols aiming to simulate entire game and/or match duration and intensity have reported changes in the sagittal plane that are indicative of an at-risk upright posture [44, 45]. However, short-term exhaustive exercise has resulted in changes in non-sagittal plane variables associated with ACL injury risk [46–50].

Trunk neuromuscular control has been implicated as a risk factor for knee injuries [51]. Compared to a more erect trunk posture, landing with the trunk relatively more flexed increases hip flexion and hip extensor moments while decreasing ground reaction forces, knee moments, and quadriceps muscle activation [33, 52]. Trunk motions during running and cutting tasks are commonly associated, with varying magnitudes, to knee abduction angles and external knee abduction moments [53–56]. However, the correlational nature of these studies does not necessarily suggest “cause-and-effect” and could potentially be the result of task-dependent associations. Together, positions and movements of segments proximal to the knee likely have the potential to place the knee joint in a position deemed at “high risk” for ACL injury.

Neurocognitive insufficiency as a risk factor of ACL injury is supported by findings of lower baseline reaction times, processing speed, and visual-spatial awareness in athletes who went on to suffer an ACL injury compared to controls [57]. Evidence for a connection of central processing to neuromuscular insufficiency is provided by findings of slower cognitive processing speed being associated with decreased trunk stability in males [58]. The keynote presentation of Dr. Buz Swanik hypothesized that such errors in judgment or coordination could lead to ill-timed large joint forces that would result in poorly controlled preprogrammed motor processes to provide dynamic restraint [59]. Such a sequence of events may adversely affect the muscles’ ability to act as an effective dynamic restraint [59].

Key Unknowns and Directions for Future Research

In order to advance the field of neuromechanical risk factors, several recurring themes were identified that need to be addressed. Importantly, external and internal loading profiles that cause noncontact ACL rupture in the field are unknown [60]. Such data would be central to optimal injury prevention strategies. Optimal ways to assess movement in the laboratory environment are still being debated with regard to single- and double-leg tasks [61, 62]. A better understanding of the actual injury event and the activities that pose the greatest loads on the ACL will better focus screening and prevention efforts. The influence of the kinetic chain (i.e., ankle, hip, lumbopelvic, and/or trunk biomechanics) on modeled ACL strain or forces has been studied in controlled movements commonly performed in rehabilitation [63, 64]. However, the specific relationship of these kinetic chain concepts to ACL injury risk is unclear. Typical biomechanical experiments rely on extracting singular measures to

Table 28.1 Neuromechanical risk factors: directions for research

• To allow us to better understand mechanisms of in vivo ACL rupture, video from actual injury situations (and control videos from these athletes before injury) must be accumulated. Additionally, cadaveric, mathematical, in vivo kinematic, and imaging research approaches should be combined to understand the postures, loads, and/or neuromuscular profiles that increase ACL strain or cause noncontact ACL rupture
• To better understand how movement patterns and other structures in the kinetic chain affect ACL loads, we must continue to develop, improve, and validate quality laboratory-based models (e.g., computational, cadaveric) that noninvasively estimate in vivo ACL forces and strain. Care should be taken to not overgeneralize results from one specific task to other tasks
• To ascertain whether kinetic chain factors are a cause or compensation for poor knee biomechanics, laboratory-, cadaver-, and/or simulation-based studies specifically designed to evaluate cause and effect (i.e., highly controlled human movement studies with one variable manipulated) are warranted
• To better understand the "richness" of biomechanical data, incorporation of alternative approaches to analyzing traditional biomechanical data (e.g., nonlinear dynamics and emerging data analyses techniques, including statistical parametric mapping) is justified
• To better understand the role of the central nervous system in ACL injury, research models should expand to include assessments of central processes (e.g., automaticity, reaction time), cognitive processes (e.g., decision making, focus and attention, prior experience [e.g., expert versus novice]), and metacognitive processes (e.g., monitoring psychomotor processes)
• Laboratory-, cadaver-, and/or simulation-based studies are needed to understand if ACL injury is a one-time event or the result of longer-term low-level loading resulting in fatigue failure of the ligament
• To better understand the role of the neuromuscular system, work on how neuromuscular properties beyond absolute strength (e.g., muscle/joint stiffness, muscle mass, rate of force production) relate to ACL function and injury risk is warranted
• To allow unique insights into observed gender differences in injury rates, examinations on the influence of the maturational process on knee biomechanics, and specifically ACL loads, are needed during the early stages of physical maturation.
• Issues related to validity and reliability need further study to trust the quality and consistency of neuromechanical data. Data processing should carefully be considered for its potential impact on identification of high-risk individuals and associations with ACL injury risk

characterize complex human biomechanics and may miss critical information on those most at risk for ACL injury. While an initial cadaveric model reported that the ACL is susceptible to fatigue failure during repetitive simulated pivot landings and a smaller ACL cross-sectional area is at greater risk for such failure [65], we do not know if it is a single episode or multiple episodes that causes gross failure of the ACL. To varying degrees, the amount of maximal strength is related to movement mechanics, although it is unclear as to how it is related to actual injury risk [66–71]. There is general consensus that maturation influences biomechanical and neuromuscular factors affecting ACL strain [72–83]. However, how maturation affects knee biomechanics in general is inconsistent [84]. Methodological concerns regarding data collection, processing, and analysis continue to confound interpretation of biomechanical variables thought to be risk factors for ACL injury. Based on these key unknowns and the many unknowns that remain, recommendations for future investigations of neuromechanical risk factors are presented in Table 28.1.

28.2.2 Anatomical and Structural Risk Factors

Anatomical and structural factors typically encompass those that are intrinsic to the body and that are generally considered to be non-modifiable through training. The primary anatomical and structural factors examined with regard to ACL injury risk include knee joint geometry, knee joint laxity, body composition, and lower extremity structural alignments. Most of the variables that comprise these anatomical characteristics differ by gender.

28.2.2.1 Current Understanding

Knee joint geometry has been studied with regard to ACL injury. The majority of prospective and retrospective case-control studies comparing joint geometry of ACL-injured patients to non-injured controls indicate that ACL-injured patients have smaller ACLs [85, 86], greater lateral posterior-inferior tibial plateau slopes (but not necessarily medial tibial slopes) [87–91], and smaller femoral notch morphology [86, 88, 92–99] compared to non-injured controls. The presence of a more prominent/thicker bony ridge on the anteromedial outlet of the femoral intercondylar notch has also been reported in ACL-injured cases versus controls [86, 88]. A reduced condylar depth of the medial tibial plateau may also be characteristic of ACL-injured cases compared to controls [87, 89, 90]. Coronal slope has not been associated with ACL injury risk [87, 89]. Multivariate analyses suggest that ACL volume, smaller inlet and outlet femoral notch widths, greater anteromedial bony ridge thickness, and posterior-inferior-directed slope of the lateral tibial compartment may independently contribute to injury risk and together provide more information on injury risk potential [86, 88, 100, 101]. However, because these multivariate analyses have varied in the geometric variables examined, there is no clear consensus regarding the unique combination of the variables that most strongly predict ACL injury risk in men and women.

When compared to males, females have smaller ACLs as assessed by length, cross-sectional area, and volume even after adjusting for body size [102]. After adjusting for age and anthropometrics, the female ACL has lower collagen fiber density (area of collagen fibers/total area of the micrograph) [103] and decreased mechanical properties such as strain at failure, stress at failure, and modulus of elasticity [104]. Females are also reported to have greater lateral and medial posterior-inferior tibial slopes [105, 106], reduced coronal tibial slopes [105], and a femoral notch height that is taller and notch width that is smaller than males [102]. While femoral notch width and angle are reported to be good predictors of ACL size (area and volume) in males but not in females [102], multivariate analyses suggest each may provide unique information [101] and collectively influence the femoral notch impingement theory [102]. Gender difference in knee structural anatomy may also explain why associations among these variables with ACL injury history are somewhat different between males and females [86, 88, 101].

Biomechanically, there is evidence that knee joint geometry is related to higher-risk biomechanics. Greater posterior-inferior lateral tibial slopes are associated with greater anterior joint reaction forces [107], greater anterior translation of the tibia relative to the femur [108, 109], and greater peak anterior tibial acceleration [110] and, when combined with a smaller ACL cross-sectional area, are associated with greater peak ACL strains [111]. Greater relative posterior-inferior slope of the lateral versus medial tibial plateau has been associated with greater peak knee abduction and internal rotation angles [107, 112], while a reduced coronal slope has been associated with greater hip adduction and knee valgus in females upon landing [112]. Collectively, there is evidence that structural characteristics of the joint may increase the risk of ACL injury and may be related to higher-risk movement biomechanics.

Joint laxity is thought to be indicative of the ability of the passive restraint system and has been commonly investigated with respect to ACL injury. Knee joint laxity varies considerably between individuals, likely due to a combination of genetic [113], hormonal [114–119], and anatomical [112, 120, 121] factors. Greater magnitudes of anterior knee laxity [98, 122, 123, 154], genu recurvatum [122, 124–127], general joint laxity [77, 122, 124, 127], and internal rotation knee laxity [128] have been reported in the contralateral knee of ACL-injured patients compared to control cases. On average, females have greater sagittal (anterior knee laxity, genu recurvatum) [98, 122, 129–133], frontal (varus-valgus rotation), and transverse (internal-external rotation) plane [119, 134–136] and generalized joint laxity compared to males [98, 122]. Gender differences in frontal and transverse plane knee laxity persist even in males and females with similar sagittal-plane knee laxity [119, 134, 136]. Females also experience increases in knee laxity across the menstrual cycle [114–119] and are more likely to experience acute increases in knee laxity during exercise [137].

Greater magnitudes of knee laxity may have both biological and biomechanical consequences. Evidence from animal studies suggest that greater knee laxity is associated with ligament biomarkers indicative of greater collagen turnover, more immature cross links, and lower failure loads [138–140]. Biomechanically, greater knee laxity magnitudes and general joint laxity have been associated with higher-risk landing strategies more often observed in females (e.g., greater knee extensor loading and stiffening and greater dynamic knee valgus), particularly in the planes of motion where greater knee laxity is observed [131, 141–147]. The acute changes in knee laxity observed during exercise and across the menstrual cycle are of sufficient magnitude to further move an individual toward higher-risk movement strategies [146–150].

Lower extremity alignment measures have also been investigated with respect to ACL injury. There is currently no clear consensus in the literature consistently linking any one lower extremity alignment factor to ACL injury. Lower extremity alignment differs between maturation groups and also develops at different rates in males and females between maturation groups [151]. Once fully matured, females have greater anterior pelvic tilt, hip anteversion, tibiofemoral angle, and quadriceps angles [130, 152]. No gender differences have been observed in measures of tibial torsion [130], navicular drop [130, 133, 152], or rearfoot angle [130, 153].

Body composition may factor into the occurrence of ACL injury. There is increasing evidence from two large prospective, multivariate risk factor studies that an elevated body mass index (BMI) may be associated, along with other factors, with an increased risk of ACL injury in females but not males [98, 154]. Higher BMI in females is more likely to represent a higher proportion of fat mass versus lean mass relative to body weight [155, 156], and less relative lean mass has been associated with greater knee joint laxity [112] and dangerous biomechanical strategies [52, 157]. This may explain why the combination of greater joint laxity and higher BMI may further increase the risk of an ACL injury in females more so than either variable alone [98, 154].

Key Unknowns and Directions for Future Research

In order to advance the field of anatomic and structural risk factors, several key areas were identified that need to be addressed. Anatomical and structural factors have often been examined independently or in small subsets of variables. Even among three larger, prospective multivariate risk factor studies [98, 154, 158], the anatomical variables examined are quite disparate, making it difficult to build a clear consensus on the best prediction model of ACL injury risk for screening purposes. Most investigations of tibial plateau geometry are based on measures of the subchondral bone, and recent research suggests that accounting for the overlying cartilage and meniscal geometry when characterizing plateau slope and depth may improve prediction [101]. Although anatomical and structural factors are often considered non-modifiable, we have limited knowledge of how these structural factors change during maturation or whether physical activity (or other chronic external loads) can influence this development over time, particularly during the critical growth periods. Recent evidence suggest that individuals with specific laxity profiles may perceive functional deficits during activities of daily living and sport [159], but it is unknown how their individual laxity profile may relate to injury risk. Based on these key unknowns and others that remain, recommendations for future investigations of anatomical and structural risk factors are presented in Table 28.2.

28.2.3 Genetic Risk Factors

ACL ruptures are multifactorial in nature, and there is increasing evidence from both familial and case-control genetic association studies that genetic sequence variants play an important role in ACL injury. Thus, there is a need to further our understanding of the genetic influences on the ACL.

28.2.3.1 Current Understanding

A growing number of common DNA sequence variants within genes involved in various biological processes have been associated with susceptibility to ACL rupture. These include variants

Table 28.2 Anatomic and structural risk factors: directions for research

• To reach consensus on measures to collect, large-scale risk factor studies that account for all relevant lower extremity anatomical and structural factors are needed. Prospective, confirmatory analyses of currently identified risk factor models across different races and ages are also needed
• Because tibial geometry measures are complex and costly, it is important to determine the extent to which these measures provide additional information on ACL injury risk once accounting for more clinically accessible risk factors
• To understand multifactorial anatomical influences on injury risk, studies examining the combined effects of joint laxity, tibial geometry (lateral tibial slope, medial/lateral tibial slope ratio, coronal slope, medial condylar depth), and ACL morphology, as well as interactions among these variables, on tibiofemoral joint biomechanics and ACL strain/failure are encouraged
• To understand the underlying factors that cause one to develop at-risk anatomical and structural profiles during maturation, prospective studies are needed that account for relevant modifiable factors such as body composition, neuromuscular properties, and physical activity
• To understand which individuals are most at risk for laxity-related ACL injury, we need to know the multiplanar laxity profiles that pose the greatest risk for ACL or the threshold at which the magnitude of knee laxity becomes problematic
• Since BMI is not a true measure of body composition or body mass distribution, future studies using a more detailed analysis of body composition are needed to fully understand how body composition contributes to faulty lower extremity biomechanics and injury risk

within several genes encoding collagens [160–166] and proteoglycans [167], which are involved in the structure and regulation of the formation of the basic building block of ligaments, namely, the collagen fibril. A subset of these variants has specifically been associated with female but not male ACL ruptures [162, 164, 165, 168]. The collagen fibril of the ACL and the other extracellular matrix components continuously remodel in response to mechanical loading for the purpose of maintaining tissue homeostasis. In support of this, variants within genes which encode proteins involved in cell signaling pathways such as angiogenesis-associated signaling [169] and the apoptosis-signaling cascade [170], as well as remodeling, specifically matrix metalloproteinases [171, 172], have also been associated with ACL ruptures.

It should also be noted that genetic association studies in humans have recently been strengthened by a publication reporting the association of variants within genes, including collagen and other genes proposed to have a detrimental effect on ligament structure and strength, with canine cranial cruciate ligament rupture (CCLR) [173]. Many of the anatomical, structural, and other risk factors are also in their own right multifactorial phenotypes determined by, to a lesser or greater extent, both genetic and environmental factors [174]. It is therefore unlikely, based on the current evidence, that the identified genetic variants are independent risk factors but rather modulate risk through their effects on structural differences and other biological variations.

Key Unknowns and Directions for Future Research

To best position the ever-expanding field of genetic research to affect a change in ACL injury, several key areas were identified that need to be addressed. Most of the genetic risk factors for ACL rupture to date have been identified in white populations, and the reported associations cannot necessarily be extrapolated to other population groups. Additionally, most of the case-control genetic association studies published to date have used relatively small sample sizes, especially with respect to the gender-specific genetic effects. It is likely that none of the associated variants alone cause ACL ruptures. Rather, the injury is a result, at least in part, of a poorly understood complex interaction of external loading and other factors, as well as intrinsic stimuli on the genetic background of the individual. Although scientists are beginning to understand the contribution of genetics to ACL injury, numerous companies are marketing direct-to-consumer genetic tests for common injuries, including ACL ruptures. These tests are premature since the genetic data is incomplete and not interpreted together with clinical indicators and lifestyle factors to identify an altered risk for injury by an appropriately qualified healthcare professional. Based on these key unknowns and the many unknowns that remain, recommendations for future investigations of genetic risk factors are presented in Table 28.3.

28.2.4 Hormonal Risk Factors

Sex hormones likely underlie many of the gender-specific characteristics that emerge during puberty. In particular, the large magnitudes and monthly variations in estrogen and progesterone concentrations that females experience continue to be an active area of ACL injury research. The hormone relaxin has also gained attention in recent years for its potential to influence ACL structural integrity and injury risk.

28.2.4.1 Current Understanding

Hormone receptors (e.g., estrogen, testosterone, and relaxin) have been localized on the human ACL [175–179], suggesting they are capable of regulating gene expression and collagen metabolism in a way that may influence the biology of the ACL and other soft tissue structures. This is supported by studies that have associated normal, physiological variations in sex hormone concentrations across the menstrual cycle with substantial changes in markers of collagen metabolism and production [180], knee joint laxity [114–119], muscle stiffness [115], and the muscle stretch reflex [181]. These biological changes may also have secondary neuromechanical consequences, as previously noted [146–150].

While prior epidemiological studies have largely suggested that the risk of ACL injury appears to be significantly greater during the preovulatory phase of the menstrual cycle compared to postovulatory phase [182–186], there has been little advancement in understanding the underlying mechanism(s). Understanding these processes is difficult given the substantial variability in the timing and magnitude of hormone changes between individuals [117], the time dependency effect for sex hormones and other remodeling agents to influence a change in ACL tissue characteristics [117, 179], and potential interactions among several sex hormones, secondary messengers, remodeling proteins, mechanical stresses, and genetic influences [117, 164, 176, 179, 180, 187–193]. As an example, interactions between mechanical stress, hormones, and altered ACL structure and metabolism have been observed in some animal models [138, 194, 195].

In recent years, the hormone relaxin has gained attention as a potential ACL injury risk factor based on a prospective study of Division I collegiate female athletes that reported elevated concentrations in those who suffered an ACL injury compared to non-injured controls [196]. While studies examining the effect of relaxin on collagen metabolism in human knee ligaments in situ are lacking, in vivo and in vitro animal studies, along with human cell culture studies, suggest that relaxin administered at physiological levels has a profound effect on soft tissue remodeling [190, 197–200]. In turn, this may lead to a less organized [201] and less dense (both in fiber diameter and density) collagen structure [190, 201] that may manifest as a weaker and more lax ACL [175]. This is supported by an animal model where guinea pig ACLs treated with relaxin at pregnancy levels were 13% more lax and 36–49% weaker [202].

Table 28.3 Genetic risk factors: directions for research

• To understand genetic markers across races, investigators should identify appropriate informative genetic markers for non-Caucasian population groups when identifying genetic risk factors for ACL ruptures in these populations
• Establishment of international consortia/registry will allow us to test the hypothesis that there is a stronger genetic contribution in individuals who tear their contralateral ACL, rather than a second tear to the same ACL or no further ACL injuries. The establishment of international consortia will also make it possible for large sample sizes to be recruited for whole genome screening methods, thereby making it possible to identify all the potentially important biological pathways involved in the etiology of ACL ruptures and how these might differ by population
• To ascertain the extent to which the associated variants may result in interindividual variation in the structure and, by implication, the mechanical properties of the ACL and surrounding tissues, as well as its responses to mechanical loading and other stimuli

Key Unknowns and Directions for Future Research

Because of the known challenges in studying hormonal effects on ACL structure and metabolism, knee joint behavior, and ACL injury risk, many questions remain. In order to advance the field of hormone research as it relates to ACL injury, several key areas were identified that need to be addressed. The understanding of biological consequences of sex hormones on collagen metabolism and the structural ACL integrity in the human knee in situ remains quite limited. While there is good evidence that some females experience substantial cyclic changes in their laxity and knee joint biomechanics across the menstrual cycle [146, 149, 150], it is not yet possible to clinically screen for these potentially "high-risk" individuals. It is unknown how the rate of increase and the time duration of amplitude peaks in hormone fluctuation across the menstrual cycle play a role in the magnitude or timing of soft tissue changes.

Additionally, much of the research to date examining the effects of hormones on soft tissues, knee biomechanics, and ACL risk are based on eumenorrheic females or assumptions of a "normal cycle." However, as many as 50% of female athletes are thought to have menstrual dysfunctions [203–205], and the effects of these menstrual disturbances on injury risk potential are relatively unknown. Also unknown is the impact of various contraceptive hormones. Although epidemiology studies have reported no protective effect of oral contraceptives against ACL injury risk [206, 207], oral contraceptives are known to vary substantially in the potency and androgenicity of the progestin compound delivered. This variation ultimately determines the extent to which they counteract the estrogenic effects [208], thus their collective impact on collagen metabolism and soft tissue properties. Furthermore, how the exogenous hormones are delivered (vaginal ring, transdermal patch, oral pills) may have varying effects on musculoskeletal tissues as they are metabolized differently [209]. Finally, when examining hormone influences in physically active females, it is important to match the complexity of intersubject differences in timing, magnitude, and interactive changes in sex hormone concentrations across the cycle to our study designs. For example, because relaxin rises and peaks over a relatively short window after ovulation based on other hormone events (6–10 days) [210–213], more precise and repeated sampling is needed to determine whether the high proportion of undetectable levels reported when obtaining a single sample (as high as 64–80%) [214–217] is due to sample timing or is indicative that some females are exposed to appreciable greater relaxin levels than others due to other mediating factors [212, 214, 218]. Based on these key unknowns and other unknowns that remain, recommendations for future investigations of hormonal risk factors are presented in Table 28.4.

Table 28.4 Hormonal risk factors: directions for Research

• To understand the increased likelihood for certain combinations of sex hormones to increase ACL injury, further studies examining the underlying gender-specific molecular and genetic mechanisms of these hormones on ACL structure, metabolism, and mechanical properties and how mechanical stress on the ACL alters these relationships and injury risk potential are needed • To best screen for at-risk individuals and prospectively examine how hormonal factors influence injury risk potential, there is a need to (1) understand the underlying processes that regulate ligament biology and resultant ligament behavior, (2) understand magnitude and timing of soft tissue changes to determine how the time of injury occurrence lines up with acute changes in ACL structure and metabolism or knee laxity changes, and (3) determine how the rate of increase or the time duration of amplitude peaks in hormone fluctuation across the menstrual cycle affects collagen metabolism and ligament biology
• There is a need to understand the impact of menstrual disturbances on injury risk potential • There is a need to better understand how the different progestins influence soft tissue structures, knee function, and ACL injury risk. Relevant comparisons should then be made between users of various hormonal contraceptives and eumenorrheic, amenorrheic, and oligomenorrheic females to determine if ACL injury risk or observed soft tissue changes vary between these groups
• To best understand hormone influences on joint function and injury risk, studies should (1) verify phases of the cycle (or desired hormone environment) with actual hormone measurements (considering all relevant hormones to include estrogen, progesterone, and possibly others) and (2) obtain multiple hormone samples over repeated days to better characterize hormone profiles within a given female [205, 219]

28.3 Screening

28.3.1 Risk Factor Screening

For effective injury prevention, prospective risk factors for ACL injury should be established before preventative measures are introduced [220]. At this juncture, it is clear that proposed risk factors for ACL injury are many and thought to include intrinsic (sex, joint anatomy, laxity, joint forces, etc.) as well as extrinsic (footwear, sporting environment, training, etc.) factors. There is a clear need to develop accurate and clinically accessible screening measures to identify those at risk of ACL injury to target these individuals specifically in our ACL injury prevention strategies.

28.3.1.1 Current Understanding

Advances in clinic- or field-based screening tools may play an important role in identifying athletes that may benefit from injury prevention programs [31]. Clinically oriented screening tools (e.g., LESS and tuck jump) show good agreement with laboratory-based biomechanics (concurrent validity) [221–224] and are sensitive in detecting changes in movement quality over time [225, 226]. However, evidence supporting the ability of clinically oriented screening tools to identify individuals at risk for future ACL injury is limited and appears to be population specific (e.g., sex, age, sport) [31, 32, 221]. For example, the LESS was reported to effectively identify elite-youth soccer athletes at higher risk of sustaining ACL injuries, with a score of 5 yielding a sensitivity of 86% and a specificity of 64% [31]. However, the LESS has not been shown to be predictive of future injury in adults [32].

Environment and age may play a role in effective screenings. Data continue to show athletes are at higher risk of ACL injury in game situations: increased game play exposure will increase ACL injury risk [227, 228]. This suggests that screening in a more “real-life” screening may be of benefit in identifying those at greatest risk of injury. Younger athletes with a previous injury history are considered at higher risk for subsequent injury [20, 229–233] and should be identified through preseason screening; especially for those participating in pivoting and cutting sports [234]. Preliminary work has demonstrated risk factors related to second injury rates including younger age, use of allograft, and tibial slope, which likely act in a multifactorial manner [235]. Additionally, biomechanical risk factors for second ACL injury during drop jumping include increased initial hip internal rotation moment in the uninvolved limb, increased peak knee valgus on the involved limb, and side-to-side asymmetries in sagittal-plane knee moment at initial contact [236].

Key Unknowns and Directions for Future Research

Given the relatively low incidence of noncontact ACL injury compared to other musculoskeletal injuries (e.g., ankle sprains), there are significant challenges in developing clinically accessible injury screening processes. We do not know what elements (e.g., specific faulty movements, combination of faulty movements, strength assessment) of clinically oriented screening tools are predictive of future ACL injury risk (predictive validity). It is unknown if biomechanical combinations known to directly load the ACL as shown in cadaver-based or simulation studies (i.e., anterior tibial shear, knee valgus, and internal rotation torque) are also effective means to screen for ACL injury. For unknown reasons, there appears to be a disconnection between the most commonly used tests to screen for ACL injury risk [237] and current evidenced-based ACL injury screening tools. Understanding this disconnect is critical to furthering ACL prevention. Further, with regard to physically mature and immature populations, there is no consensus as to whether prospective risk factors of ACL injury are the same or different. Based on these key unknowns and the many unknowns that remain, recommendations for future investigations of ACL risk factor screening are presented in Table 28.5.

Table 28.5 Risk factor screening: directions for research

• To best effectively predict ACL injury risk, there is a need to develop clinically oriented screening tools that have good sensitivity and specificity • To better assess ACL injury risk, the use of novel wearable sensors and advanced in-game monitoring may play an important role
• Given the relatively low incidence of ACL injury, multi-site clinical investigations identifying ACL injury risk factors are necessary to best identify those at risk
• We need to determine if prospective risk factors for ACL reinjury are similar to those of the initial ACL injury • To best understand ACL injury with respect to age, maturation, sex, sport, and experience level, epidemiologic studies need to be performed in a variety of populations

28.4 Injury Prevention

28.4.1 ACL Injury Prevention

Various injury prevention programs have been shown to reduce the incidence of ACL injuries. However, overall ACL injury rates and the associated gender disparity have not yet diminished. There is still much we need to learn to maximize the effectiveness of these programs and to identify highly sensitive screening tools to target prevention efforts toward those at greatest risk for injury.

28.4.1.1 Current Understanding

A variety of ACL injury prevention programs that incorporate elements of balance training, plyometric training, education, strengthening, and technique training/feedback have been shown to reduce ACL injury in females [184, 238–245] or alter biomechanical and neuromuscular variables thought to contribute to ACL injury [221, 246–254]. Injury prevention training programs with successful outcomes (e.g., injury rate reduction, improvement in neuromuscular control or performance) are performed 2–3 times per week and last between 15 and 60 min [184, 221, 238, 240, 242, 243, 247, 249–251, 254, 255]. With regard to males, the most frequently implemented exercises in soccer to prevent noncontact injuries involve eccentric exercise (in general), balance, and specific hamstring eccentrics [237]. However, data regarding the effectiveness of prevention programs to reduce ACL injuries are not conclusive as to recommendations for future work including single-leg and multidirectional maneuvers [256, 257] or recommendations for prevention in male athletes.

Retention and transference are important concepts in determining the effectiveness of prevention programs. Improvements in movement quality after 12 weeks of training do not appear to be retained once ceasing preventive training programs [226]. Thus, optimal results for retention and transfer require effective training principles that entail sufficient practice, variation, and frequency [226]. Recent research has focused on improving the delivery of prevention programs. For example, feedback should emphasize successful performance and ignore less successful attempts; this benefits learning because of its positive motivational effects [258]. Programs that focus on correcting individualized techniques also appear to be successful [259–261]. Real-time feedback has also been used to positively affect landing biomechanics [262–265]. However, expert plus self-modeling seems to be most effective in changing landing biomechanics [254, 260, 266–268]. Additionally, prevention programs can be delivered with an internal focus of attention (IF, focus on the movements themselves, e.g., “flex your knees when landing”) or with an external focus of attention (EF, focus on the movement effect, e.g., “touch target as you land”) [269]. The age demographic of the group should also be considered as age-appropriate injury prevention training programs can be effective at modifying biomechanics in children [225, 270].

Compliance strongly influences the success of ACL injury prevention programs [271, 272]. However, knowledge and beliefs may not impact program adherence [271, 273], so other motivational factors must be considered. Coaches are hesitant to implement ACL injury prevention programs because they may feel it is “too much,” not of their primary interest [273–275], does not offer a relative advantage over their existing practices, does not align with their needs, or is too complex to implement in their setting [276]. However, having support from coaches and having a senior position in the hierarchy to successfully influence the prevention program are extremely important [277]. Athletes are willing to perform a lower extremity injury prevention program if data indicate that the program could improve performance factors and lead to fewer injuries [278].

Increasing or maintaining athlete performance is a crucial part of injury prevention because trainers and coaches are more likely to adopt an injury prevention program that does not conflict with performance [279]. It is important to note that injury prevention training can be used to improve performance such as vertical jump height, strength, and running speed [255, 259, 260, 269, 280]. Established frameworks could greatly help in organizing future research endeavors in large-scale injury prevention implementation efforts [281, 282]. Collectively, injury prevention programs are important because on average, the implementation of a universal training program would save $100 per player per season and would reduce the incidence of ACL injury from 3% to 1.1% per season [283].

Key Unknowns and Directions for Future Research While ACL injury prevention programs are successful in reducing the risk of ACL injury, the ideal combination and emphasis of training components within these programs need to be further delineated [272, 284–286]. It is not known which specific program element(s) is/are responsible for the reduced injury risk or biomechanical changes. Further, it is unknown how to effectively implement multifaceted programs in different settings that are sustainable over time that result in widespread implementation with high compliance rates and retention over the long term. Additionally there is uncertainty as to how a participant's sex, age, skill level, and type of sport should be considered in the type and variety of exercises prescribed and technique training/feedback provided. While anatomical and structural factors influence weight bearing knee joint neuromechanics [107, 110, 111, 144, 145, 150], ACL prevention efforts have not accounted for individual anatomical and structural factors. Finally, given that athletes with a previous ACL injury are at higher risk for subsequent injury [20, 229–233], prevention of subsequent ACL injuries should also be considered in this population.

While technique training and feedback are frequently provided during injury prevention training programs to improve movement patterns, little is understood regarding which means of technique training is most effective. While the motor learning literature has studied many aspects of feedback and the effectiveness of various feedback [260, 269, 287], ACL prevention programs have not widely integrated fundamental motor learning principles.

From a public health perspective, it is unknown of which characteristics of prevention programs make them most "palatable" to the public that subsequently will improve wide-scale implementation and adequate compliance. There is clinical potential that ACL prevention programs may also serve to prevent other musculoskeletal conditions which would serve to improve the public implementation of such programs. Based on these key unknowns and the many unknowns that remain, recommendations for future investigations of ACL injury prevention screening are presented in Table 28.6.

28.5 Global Observations

In building upon the specific understanding and unknowns presented above, there were some global themes that emerged from the meeting that do not neatly fit into a singular category. As our understanding of ACL injury risk and prevention grows, it is becoming increasingly apparent that ACL injury mechanism(s) are multifactorial, resulting from the interplay of neuromuscular, biomechanical, anatomical, genetic, hormonal, and other factors. Although we have learned much in recent years about gender differences in neuromechanical movement patterns

Table 28.6 ACL injury prevention: directions for research

• To understand optimal design and delivery of ACL prevention programs, we need to research the essential components (e.g., strengthening, plyometrics, etc.) and training stimuli (frequency, intensity, duration) of successful programs that produce desired protective effects
• To understand feasibility of widespread adoption of injury prevention programs, prepackaged preventive training programs need to be developed that can be implemented broadly across different settings through appropriately educated and trained coaches or team leaders and designed with compliance and efficacy in mind. Such studies should investigate time demands, delivery of program (e.g., coaches instead of athletic trainers or strength and conditioning specialists), outcomes, and means to educate stakeholders to approve adoption and adherence • To help with coach/team compliance, there is a need to continue to investigate the performance enhancement benefits associated with regularly performing preventive training programs
• To best serve various demographics, the most impactful age or stage of maturation and development at which to begin implementing injury prevention training programs should be determined
• To determine the most efficacious means by which to positively impact learning of technique, there is a need to study which feedback modalities (e.g., virtual reality, real-time feedback, and portable technologies) are most effective • To improve short-term acquisition and transference, as well as longer-term retention of motor techniques associated with injury prevention, there is a need to investigate the means of instruction (e.g., internal focus vs. external focus) by which technique is taught
• To help eliminate the risk of a subsequent ACL injury, further prevention research should be targeted to those individuals who have sustained an initial ACL injury

and the external loading factors that strain the ACL, far less is known about the factors that contribute to an inherently structurally weaker ligament. This is important, because the impact of external loading factors on injury risk potential (i.e., the potential to cause ligament failure) is likely dependent on the intrinsic properties (thus structural integrity and load-bearing capabilities) of the ligament. From this perspective, new evidence continues to emerge as to the potential for an athlete's genetic makeup and hormone profile to substantially alter the structural properties of the ACL, making it more or less vulnerable to failure with external loading. This interplay between external loading and intrinsic ligament properties may explain why screening on movement patterns alone has yet to yield consistent and reliable risk factor prediction models. Additionally, there was a building consensus among attendees that the risk factors may not be the same for males and females. As such, examining this interplay would also help us further elucidate whether females are at greater risk of noncontact ACL injury due to female-specific injury mechanisms or if the same external loading injury mechanisms apply but the underlying intrinsic risk factors are merely more prevalent in females.

Despite the likely multifactorial nature of this injury, studies of isolated risk factors (e.g., anatomic, hormonal, genetic, kinematic, or kinetic) continue to dominate the literature. Further, because of the relatively low incidence of ACL injury, lower extremity biomechanics are often studied as outcome measures to represent ACL injury potential based on what we have learned from cadaveric ligament-loading studies. If we are to fully understand the movement behavior resulting in elevated ACL loading, researchers need to study ACL injury as the outcome and move toward a more comprehensive assessment of both the non-modifiable (anatomy, genetics, and hormones) and modifiable (neuromechanics) factors that influence risk. Conducting such multifactorial studies with injury as the outcome will allow us to determine important interactions and interdependencies among the various risk factors and also identify the unique combination of factors that can most reliably predict future injury risk potential in the simplest way possible. Although there remain tremendous challenges in performing such large-scale multivariate risk factor studies (e.g., funding, personnel, and geographic restrictions), results from these types of studies are beginning to emerge. Additional and important insights of injury risk are also being gained from the studies of the incidence and predictors of a second ACL injury after primary ACL reconstruction and full return to sport participation [235]. Studying risk factors of repeat ACL injury after primary ACL reconstruction may lend further insight to risk factors of the primary injury.

28.6 Summary

Once again, we find that in the 3 years since the last ACL Research Retreat, there have been many advances in our knowledge that have shaped what we know about ACL injury risk and prevention and the important directions for future research that are needed to move the field forward. It is our hope that these proceedings will continue to stimulate quality research to more effectively identify those at risk before an injury occurs and promote high-quality clinical interventions.

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