Frank R. Noyes
Sue Barber-Westin
Editors

ACL Injuries in the Female Athlete

Causes, Impacts, and Conditioning Programs

With DVD-ROM

Springer

ACL Injuries in the Female Athlete

Frank R. Noyes • Sue D. Barber-Westin
Editors

ACL Injuries in the Female Athlete

Causes, Impacts, and Conditioning Programs

Springer

Editors
Frank R. Noyes, M.D.
Cincinnati Sportsmedicine Research and Education Foundation
Cincinnati, Ohio
USA

Sue D. Barber-Westin, B.S.
Cincinnati Sportsmedicine Research and Education Foundation
Cincinnati, Ohio
USA

ISBN 978-3-642-32591-5 ISBN 978-3-642-32592-2 (eBook)
DOI 10.1007/978-3-642-32592-2
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2012955470

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

The dilemma of the gender disparity in anterior cruciate ligament (ACL) injuries began nearly 20 years ago when unsettling data began to appear in the *American Journal of Sports Medicine* from the editors' orthopedic and sports medicine center and the National Collegiate Athletic Association:

> The injury rate of serious knee ligament injuries among female athletes was 5.75 times that of male athletes, a difference that proved to be statistically significant (1994) [6].
> Specifically, female soccer players had an ACL injury rate at least twice as high as male players in any given year. Female basketball players had an ACL injury rate at least three times that of male players in 4 of the 5 years sampled (1995) [1].

Although no scientific data existed to determine why female athletes in certain sports were suffering higher rates of ACL injuries than their male counterparts, there were enough theories of causative risk factors to support the initiation of special training programs designed to decrease this problem;

> One starts an action simply because one must do something.
>
> – T.S. Eliot

Although it may have seemed premature to promote training of female athletes involved in soccer, basketball, and other high-risk activities, a few pioneers set forth to improve or change aspects of these athletes' movement patterns that seemed to inherently predispose them for ACL injury:

> This training may have a significant effect on knee stabilization and prevention of serious knee injury among female athletes (1996) [3].

> This prospective study demonstrated a decreased incidence of knee injury in female athletes after a specific plyometric training program (1999) [4].

Following the publication in 1999 of a neuromuscular training program that reduced the incidence of ACL injuries in female high school athletes, this topic generated tremendous interest almost instantly. Researchers from around the world were soon involved in studying risk factors hypothesized to cause the gender disparity and developing other training programs designed to reduce the incidence of noncontact ACL injuries. At the time of writing, over 300 original research investigations had been published that focused on ACL injuries in the female athlete.

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. There is little doubt that the findings first described in 1994–1995 did not represent a trend or fad but a truly important problem worthy of bringing the interest of the best minds involved in sports medicine to try to solve or reduce this problem. In fact, multiple "ACL research retreats" (occurring in 1999, 2001, 2003, 2005, 2006, 2008, 2010, 2012) and consensus statements from organizations such as the International Olympic Committee [7] demonstrate the attention and emphasis the female athlete ACL injury dilemma has received internationally.

As shown in this textbook, many more investigators are studying the causative factors producing the higher incidence of ACL injuries in female athletes than are involved in prevention training. Debate exists regarding the continuing problem of deciphering the true risk factors, and in fact, there remain questions on the exact mechanisms of this injury. Public health experts stress the critical need to understand the etiology of why athletic injuries occur because

> Prevention cannot be instigated until this information is available because the specific focus and targeting of prevention programs is unclear [2].

So, at least for ACL injuries, a paradox exists in that we are still in the process of understanding the mechanisms and risk factors for the injury, yet prevention programs have reduced the incidence in some female athletic populations. This is true both for a few individual training programs and for meta-analyzed data:

> The findings from this review lend support to ACL injury prevention programs designed to prevent unopposed excessive quadriceps force and frontal-plane or transverse plane (or both) moments to the knee and to encourage increased knee flexion angle during sudden deceleration and acceleration tasks (2008) [9].

> Our study indicated strong evidence in support of a significant effect of ACL injury prevention programs. Our pooled estimates suggest a substantial beneficial effect of ACL injury prevention programs, with a risk reduction of 52% in the female athletes and 85% in the male athletes (2012) [8].

If it seems we are getting ahead of ourselves, that may be true. However, the ever-growing interest in ACL injury prevention training is indicative that many health professionals, athletes, coaches, and parents believe that some type of preventative effort is better than nothing. In fact, the editors' nonprofit research foundation has certified over 1,360 individuals to conduct neuromuscular ACL injury prevention programs in their communities and medical practices. A recent Bing search of "ACL Injury Prevention Training" revealed 515,000 hits, highlighting the popularity of this topic.

Unfortunately, not everyone has jumped on the bandwagon regarding ACL injury prevention training. Many authors have noted problems convincing coaches to agree to add this type of training to their practice schedules or to train their athletes before the season begins. In a recent study [5], 258 high school coaches in the Chicago area were invited to participate in a coach-led ACL injury prevention training program. Only 95 (37 %) enrolled. 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 solution is to study and identify 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, force plate, 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.

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.

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. We agree with a recent consensus statement that we need to consider

> …increasing our focus on the youth athlete and taking more of a public health approach in our injury-risk screening and injury-prevention strategies in this population [10].

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.

Frank R. Noyes, M.D.
Sue D. Barber-Westin, B.S.

References

1. Arendt E, Dick R (1995) Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. Am J Sports Med 23(6):694–701
2. Finch C (2006) A new framework for research leading to sports injury prevention. J Sci Med Sport 9(1–2):3–9; discussion 10
3. Hewett TE, Stroupe AL, Nance TA et al (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24(6):765–773

4. Hewett TE, Lindenfeld TN, Riccobene JV et al (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27(6):699–706
5. Labella CR, Huxford MR, Grissom J et al (2011) Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. Arch Pediatr Adolesc Med 165(11):1033–1040
6. Lindenfeld TN, Schmitt DJ, Hendy MP et al (1994) Incidence of injury in indoor soccer. Am J Sports Med 22(3):364–371
7. Renstrom P, Ljungqvist A, Arendt E et al (2008) Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. Br J Sports Med 42(6):394–412
8. Sadoghi P, von Keudell A, Vavken P (2012) Effectiveness of anterior cruciate ligament injury prevention training programs. J Bone Joint Surg Am 94(9):769–776
9. Shimokochi Y, Shultz SJ (2008) Mechanisms of noncontact anterior cruciate ligament injury. J Athl Train 43(4):396–408
10. Shultz SJ, Schmitz RJ, Nguyen AD et al (2010) ACL Research Retreat V: an update on ACL injury risk and prevention, March 25–27, 2010, Greensboro, NC. J Athl Train 45(5):499–508

Contents

Acronyms

ACL	Anterior cruciate ligament
AE	Athlete-exposure
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
CD	Compact disc
CNS	Central nervous system
cm	Centimeters
COF	Coefficient of friction
COM	Center of mass
COP	Center of pressure
COMP	Cartilage oligomeric matrix protein
DEXA	Dual energy x-ray absorptiometry
DPSI	Dynamic postural stability index
EMG	Electromyographic or electromyography
ER	External rotation
FAST-FP	Functional Agility Short-Term Fatigue Protocol
FIFA	Federation Internationale de Football Association
FPPA	Frontal plane projection angle
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
IC	Initial contact
ICC	Intraclass correlation coefficients
IEMG	Integrated electromyography
IKDC	International Knee Documentations Committee
IR	Internal rotation
IR/ER	Internal rotation / external rotation

H:Q	Hamstrings-to-quadriceps
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
min	Minutes
MMPs	Metalloproteinases
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	Newtons
Nm	Newton meters
OA	Osteoarthritis
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
QH	Quadriceps-hamstrings
RM	Repetition max
s	Seconds
SEBT	Star Excursion Balance Test
SEPs	Somatosensory evoked potentials
SLO-FP	Slow Linear Oxidative Fatigue Protocol
SPECT	Single-photon emission computed tomography
STG	Semitendinosus-gracilis
TIMP	Tissue inhibitors of metalloproteinases
TDPM and TTDPM	Threshold for detection of passive motion
TRIPP	Translating Research into Injury Prevention Practice
TTDPM	Threshold to detect passive motion
U.S.	United States
vGRF	Vertical ground reaction force
VMO	Vastus medialis oblique
VO_2max	Maximal oxygen uptake
WIPP	Warm-up for Injury Prevention and Performance
wk	Week
×	Times
yr	Year
3-D	3 dimensional
2-D	2 dimensional

Part I

Introduction

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

1

Frank R. Noyes and Sue D. Barber-Westin

Contents

F.R. Noyes, M.D.
Cincinnati Sportsmedicine and Orthopaedic Center, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Cincinnati Sportsmedicine Research and Education Foundation,10663 Montgomery Road, Cincinnati, Ohio 45242, USA

S.D. Barber-Westin, B.S. (✉)
Cincinnati Sportsmedicine Research and Education Foundation,
10663 Montgomery Road, Cincinnati, Ohio 45242, USA
e-mail: sbwestin@csmref.org

Introduction

Anterior cruciate ligament (ACL) tears are the most common, complete ligamentous injuries that occur in the knee joint. In the United States (US), ACL tears occur in an estimated 1 in 3,500 individuals each year [6], and although exact data are not currently available, it is believed that approximately 125,000–200,000 ACL reconstructions are performed annually. Few national registries exist to document ACL injuries and reconstructions. The National Survey of Ambulatory Surgery from the US reported that 127,446 ACL reconstructions were performed in 2006 [41]. The Swedish National Registry was used to calculate the incidence of ACL injury in 2002, which was 0.81/1,000 inhabitants per year in individuals aged 10–64 years [29], with over 3,000 reconstructions performed annually [43]. In Norway, the annual incidence of cruciate reconstructions from 2004 to 2006 was reported to be 85 per 100,000 in citizens 16–39 years old [31]. The annual rate of cruciate reconstructions in this age group was 1,168. In the United Kingdom, a trauma institution that treated all adults from a population of 535,000 reported an ACL injury rate of 8.1 per 100,000 citizens per year [20]. The population in that investigation was 13–89 years old. It is reasonable to estimate that one million ACL injuries occur yearly worldwide.

Regardless of nationality, the majority of patients who sustain ACL injuries and undergo reconstruction are athletes <25 years old who are frequently involved in high school, collegiate, or

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_1,

league sports [93]. At least two-thirds of ACL tears occur during noncontact situations while an athlete is cutting, pivoting, accelerating, decelerating, or landing from a jump [13, 15, 84]. The costs of treatment of ACL tears are substantial, and athletes who suffer concomitant meniscus tears that require resection or other ligament tears are at increased risk for premature osteoarthritis [2, 34]. As well, athletes may suffer from deterioration of emotional health regardless of the treatment of the ACL injury [17, 46, 63, 73, 91].

The initial reports of a higher incidence of noncontact ACL injuries in female athletes compared to male athletes participating in soccer and basketball appeared in the medical literature in 1994 [50] and 1995 [4]. Since then, researchers worldwide have spent considerable time and effort in attempting to understand why this disparity exists in these and other sports and if interventions such as neuromuscular retraining can lessen the difference in injury rates between genders.

Critical Points

- United States: ACL injuries ~1 in 3,500 individuals; 125,000–200,000 ACL reconstructions annually.
- Swedish National Registry: >3,000 ACL reconstructions annually.
- Norway: patients 16–39 years old: 1,168 ACL reconstructions annually.
- Worldwide: one million ACL injuries annually.
- Majority are athletes <25 years old involved in high school, collegiate, or league sports.

Anatomy

Overview

Many authors have described the anatomy of the ACL [89]. The ACL is an average of 38 mm in length and 11 mm in width. This ligament originates on the medial aspect of the lateral femoral condyle (Fig. 1.1). The 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 (termed the resident's ridge) [40] that is anterior to the posterior cartilage of the lateral femoral condyle (Fig. 1.2).

The insertion of the ACL, which is a roughly oval to triangular pattern, is located in the anterior intercondylar area of the tibia (Fig. 1.3). The insertion fans out and has been described as resembling a "duck's foot" (Fig. 1.4) [77]. 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, which is referred to as the intercondylar eminence in anatomy textbooks (Fig. 1.5) [21, 88]. The medial and lateral tibial spines are referred to as the medial and lateral intercondylar tubercles [21]. 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 (Fig. 1.6).

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. [3] and Colombet et al. [23] are among those who state that the anteromedial (AM) bundle functions as the proximal half of the attachment that tightens with knee flexion. In contrast, the posterolateral (PL) bundle 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 the tightening and relaxation of the AM and PL bundles represents that which occurs under no loading conditions in the laboratory. When

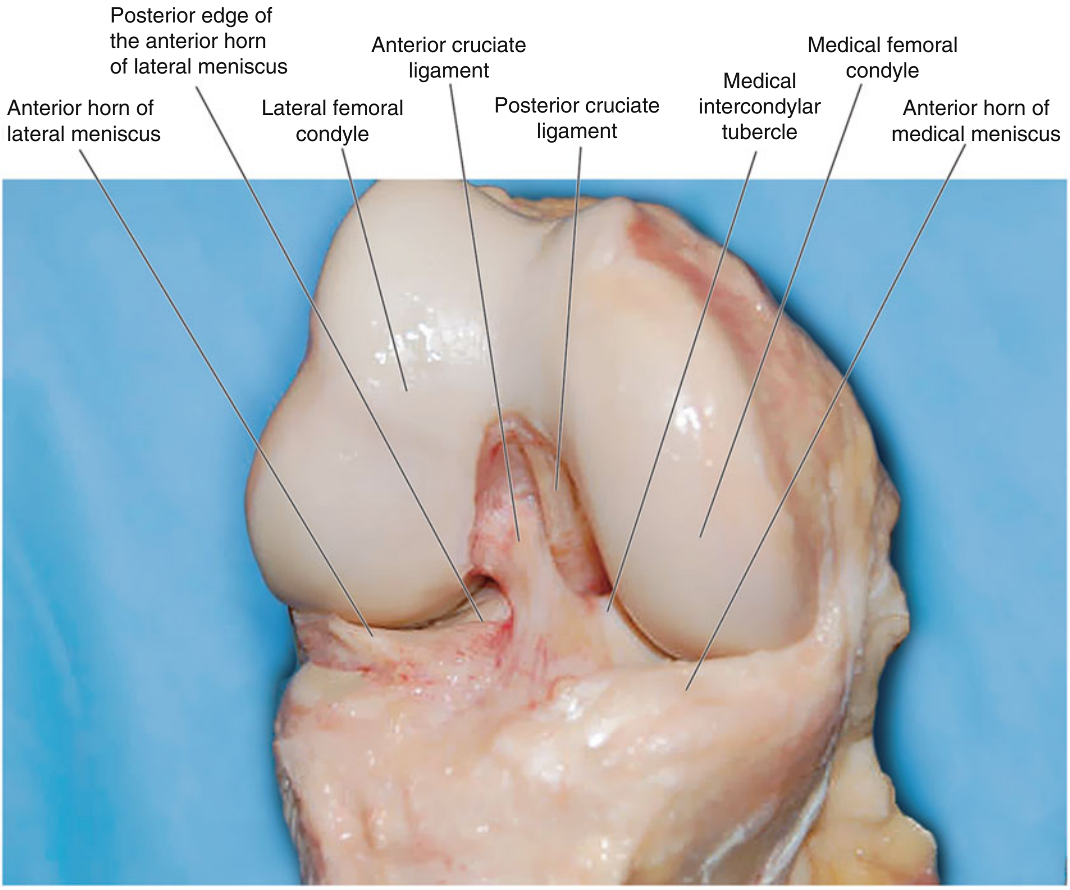


Fig. 1.1 Anterior view of the knee demonstrating the oblique orientation of the ACL originating on the medial aspect (sidewall) of the lateral femoral condyle (Reprinted with permission from Strickland et al. [89])

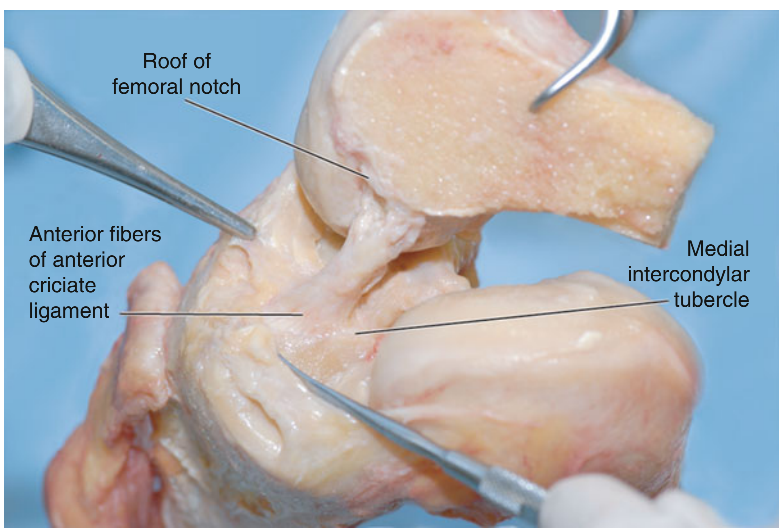


Fig. 1.2 Lateral view of the ACL. Note the distance from the posterior cartilage of the lateral femoral condyle to the ACL (Reprinted with permission from Strickland et al. [89])

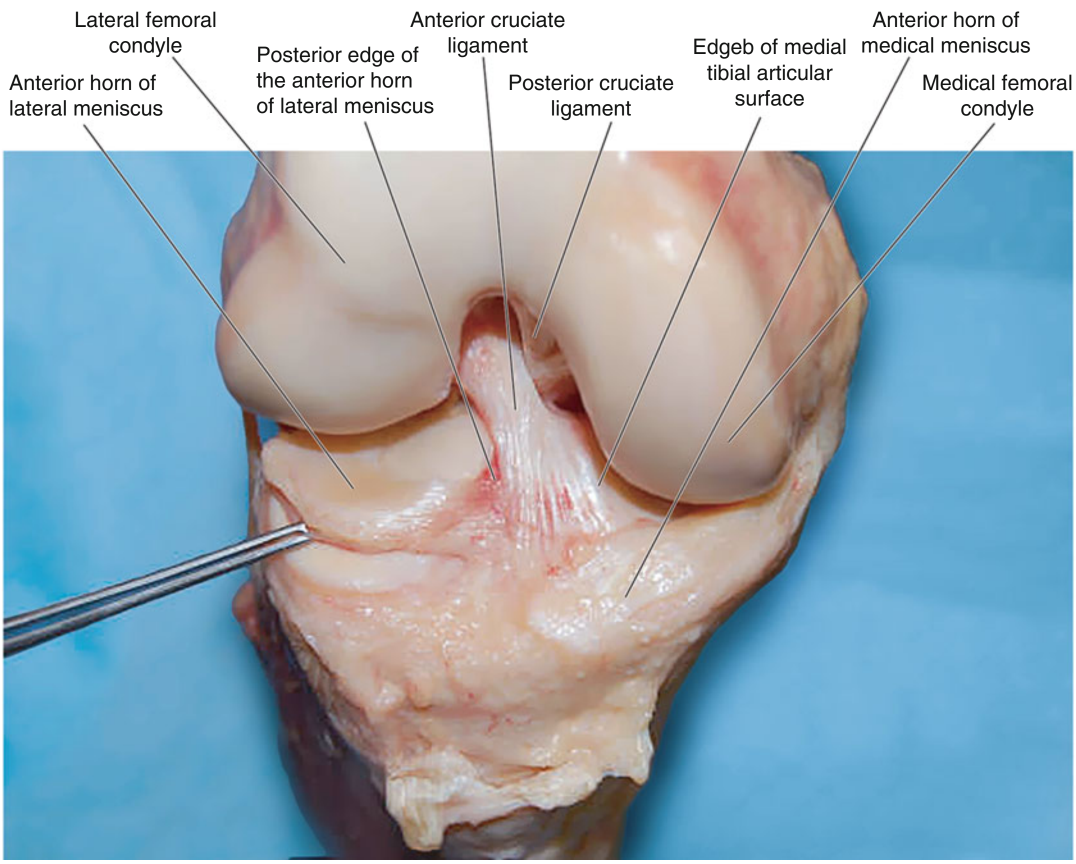


Fig. 1.3 Anterior-superior view of the knee demonstrating the ACL tibial insertion (Reprinted with permission from Strickland et al. [89])

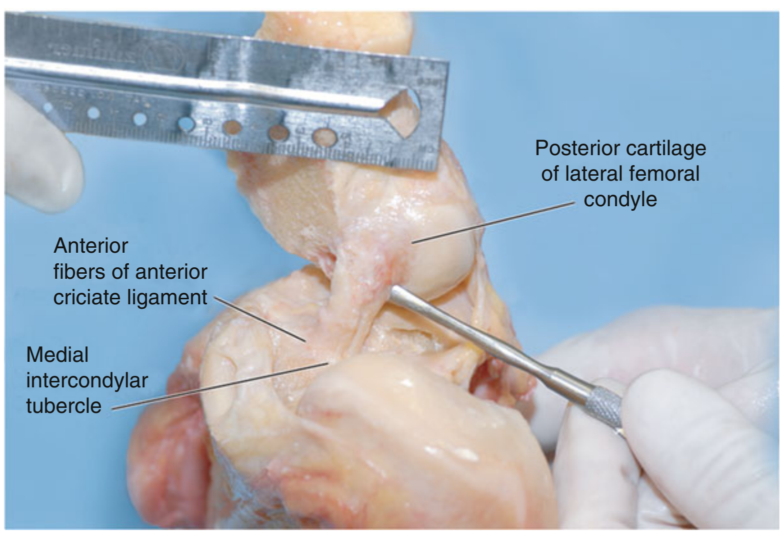


Fig. 1.4 Lateral view of the ACL. The anterior extension of the tibial insertion of the ACL is well visualized (Reprinted with permission from Strickland et al. [89])

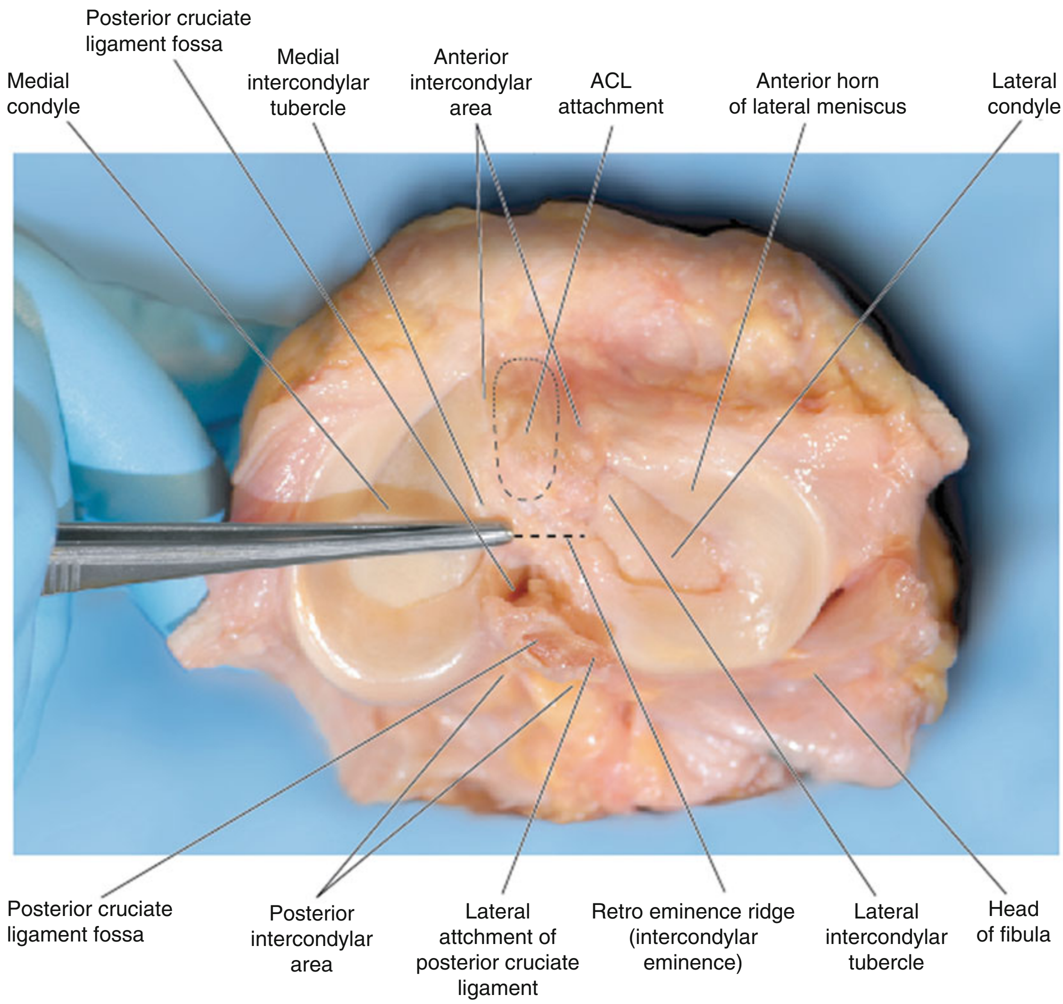


Fig. 1.5 Axial photo of the tibial plateau demonstrating the anterior insertion of the ACL. Notice the ACL's tibial insertion in relation to the medial tibial spine and the retro-eminence ridge (Reprinted with permission from Strickland et al. [89])

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 [69].

The authors believe the classification of the ACL as a structure comprised of two fiber bundles represents a gross oversimplification not supported by biomechanical studies [37, 69, 71, 86]. 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 AM and PL divisions contribute to resist tibial displacement. 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. 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 [13, 69].

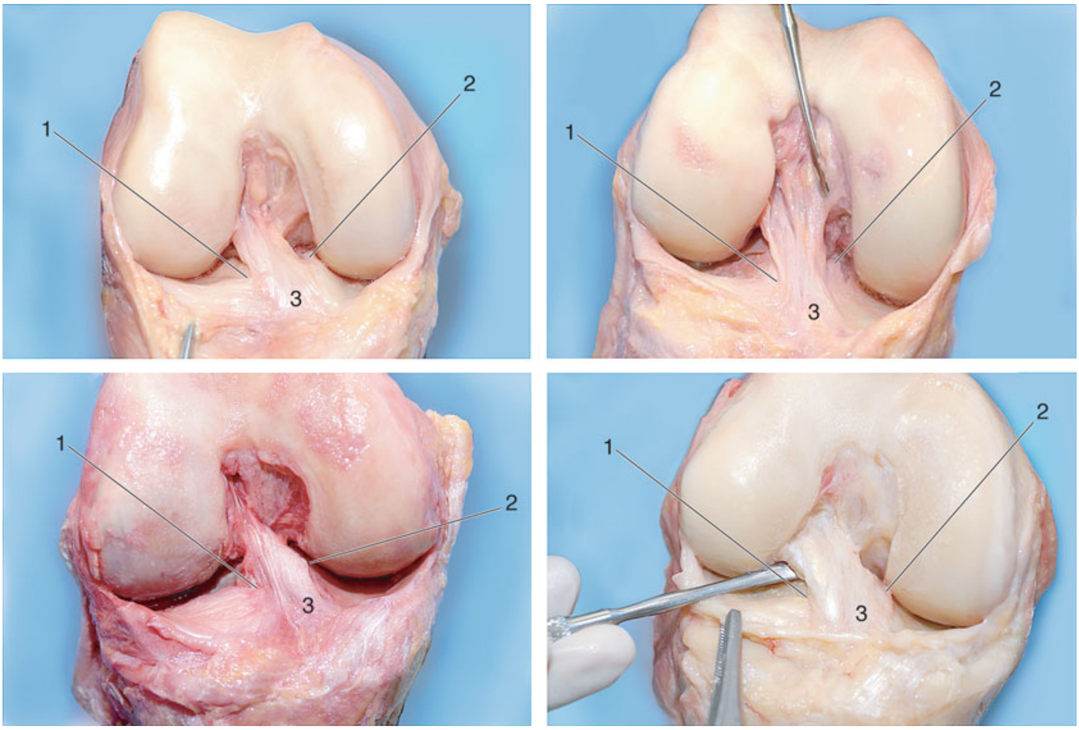


Fig. 1.6 Anterior-superior views of a series of four knees showing that >50 % of the ACL (*3*) inserts anterior to the posterior edge of the anterior horn of the lateral meniscus (*1*). Medial intercondylar tubercle (*2*) (Reprinted with permission from Strickland et al. [89])

Critical Points

ACL

- Mean length 38 mm, width 11 mm.
- Origin on medial aspect of lateral femoral condyle, 18 mm long and 10 mm wide.
- Insertion on tibia in anterior intercondylar area, oval-triangular pattern, anteroposterior dimension 18 mm, mediolateral dimension 10 mm.
- Anterior border 22 mm from anterior cortex of tibia, 15 mm from anterior edge of articular surface.
- 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 occurs under no anterior loading conditions.
- Under loading conditions, majority ACL fibers are in load sharing configuration.
- Characterization ACL into two fiber bundles: gross oversimplification, not supported by biomechanical studies.

Biomechanics

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. 1.7 and 1.8) [18]. The secondary restraint to anterior tibial translation is provided by the iliotibial band, mid-medial capsule, mid-lateral capsule, medial collateral ligament, and fibular collateral ligament. The posteromedial

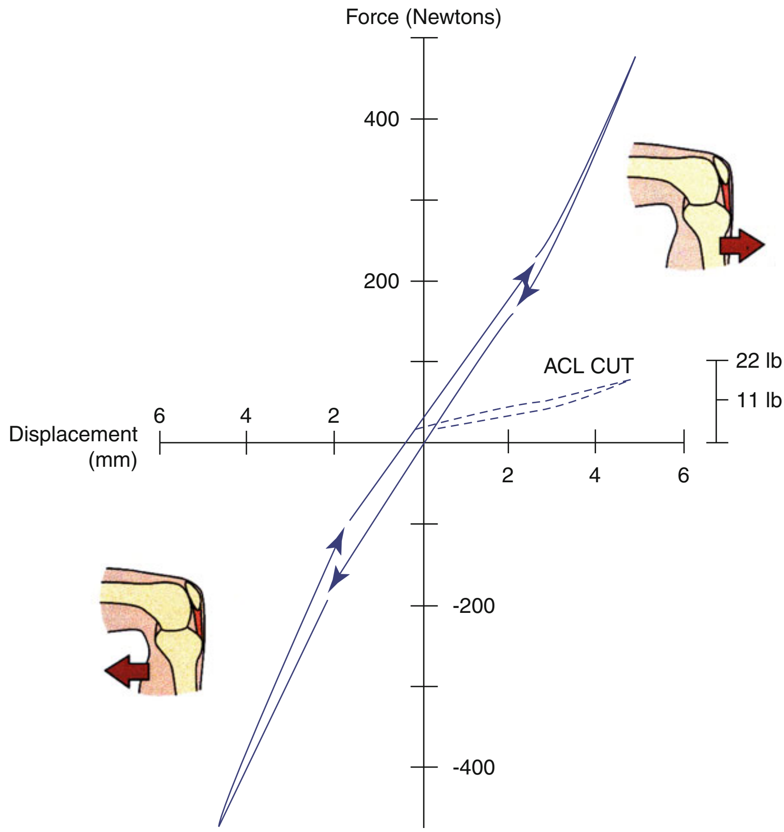


Fig. 1.7 A typical force-displacement curve for anterior-posterior drawer in an intact joint (*solid line*) and after cutting the ACL (*broken line*). The *arrows* indicate the direction of motion (Reprinted with permission from Noyes and Grood [71])

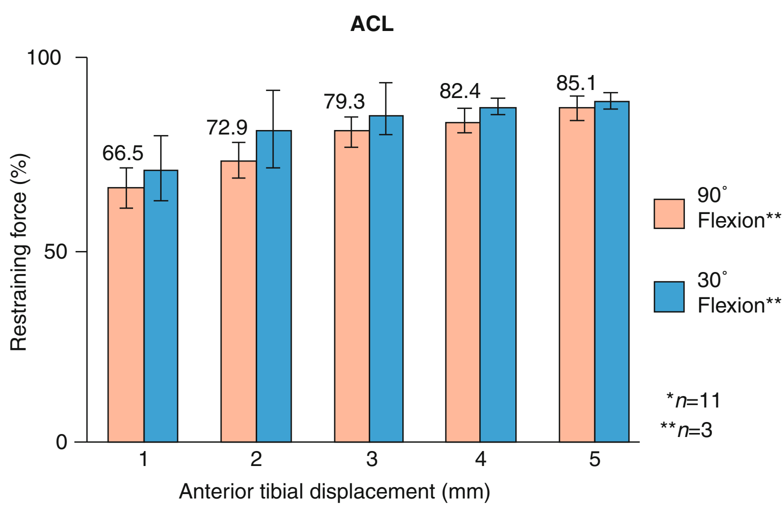


Fig. 1.8 Anterior drawer in neutral tibial rotation. The restraining force of the ACL is shown for increasing tibial displacements at 90° and 30° of knee flexion. The mean value is shown, plus or minus 1 standard error of the mean. Percentage values are given for 90° of flexion. No statistical difference was found between 90° and 30° or between 1 and 5 mm of displacement (Reprinted with permission from Noyes and Grood [71])

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 symptoms. The failure load and stiffness values of the ACL are 2,160 ± 157 N and 242 ± 28 N/mm, respectively [92]. These values decrease with age [70].

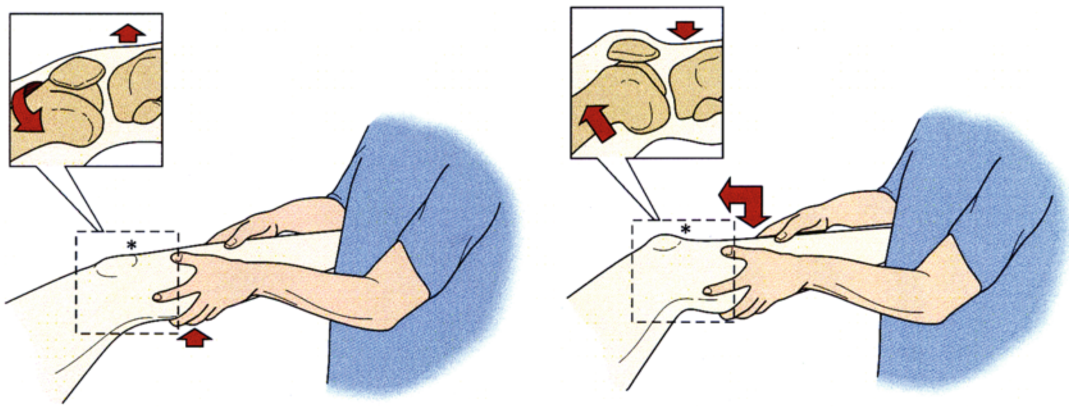


Fig. 1.9 (*Left*) Flexion-rotation drawer test, subluxated position. With the leg held in neutral rotation, the weight of the thigh causes the femur to drop back posteriorly and rotate externally, producing anterior subluxation of the lateral tibial plateau. (*Right*) Flexion-rotation drawer test, reduced 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 with permission from Noyes and Grood [71])

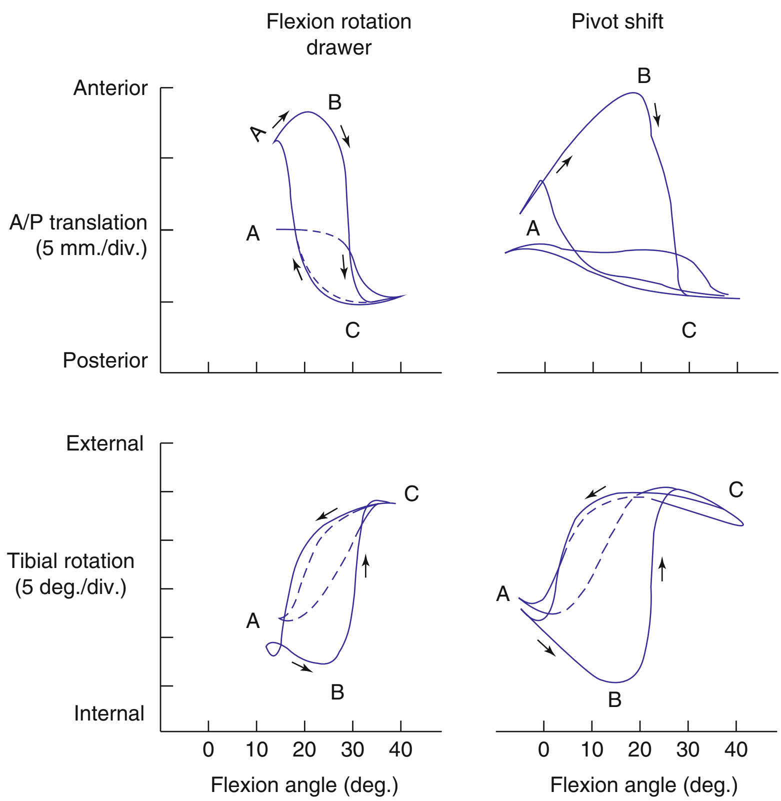


Fig. 1.10 The knee motions during the flexion-rotation drawer and pivot shift tests are shown for tibial translation and rotation during knee flexion. The clinical test is shown for the normal knee (*open circle*) and after ligament sectioning (*dotted circle*). The ligaments sectioned were the ACL, iliotibial band, and lateral capsule. Position *A* equals the starting position of the test, *B* is the maximum subluxated position, and *C* indicates the reduced position. The pivot-shift test involves the examiner applying a larger anterior translation load which increase the motion limits during the test (Reprinted with permission from Noyes and Grood [71])

The ACL limits the combined motions of internal tibial rotation and anterior translation of the tibia, as measured by the pivot-shift and/or flexion-rotation drawer tests [66, 67]. The motions that occur during the pivot-shift maneuver are shown in Figs. 1.9 and 1.10 [69]. In a knee with an ACL rupture, an increase in both anterior tibial translation and internal tibial rotation occurs as the femur drops back posteriorly and externally rotates, causing an

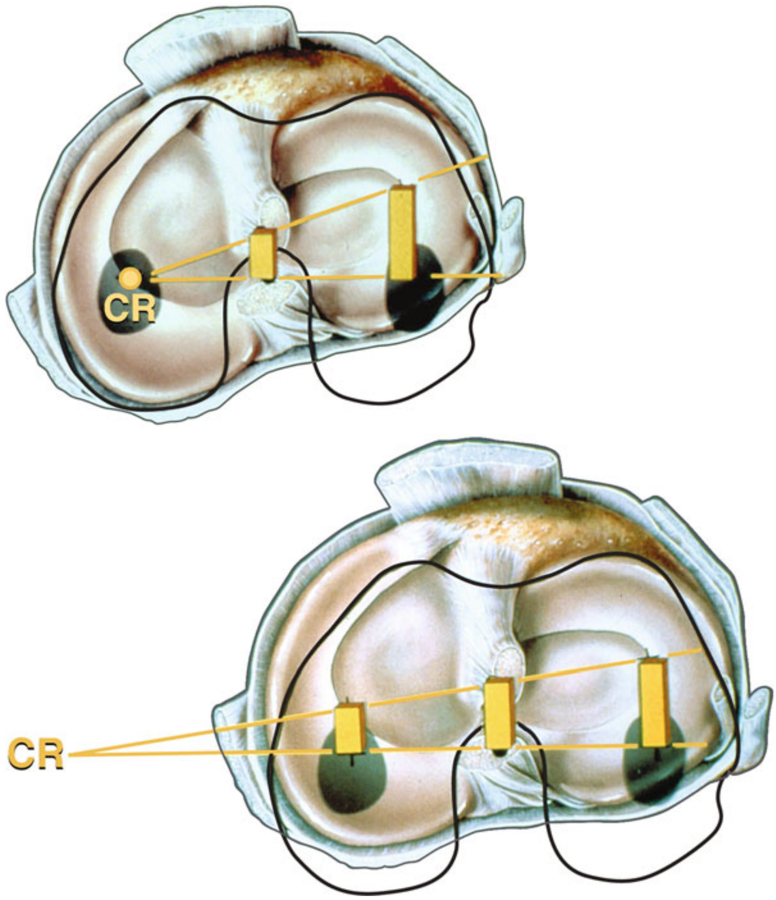


Fig. 1.11 Intact knee and after ACL sectioning: response to coupled motions of anterior tibial translation and internal tibial rotation. *Top*, Intact knee. The center of rotation may vary between the medial aspect of the PCL and meniscus border, based on the loads applied and physiologic laxity of the ligaments. *Bottom*, 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 compartment 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 with permission from Noyes and Barber-Westin [69])

anterior subluxation of the lateral tibial plateau. This position is heightened as the tibia is lifted anteriorly.

The ACL also provides rotational stability to the combined motions of anterior translation and internal tibial rotation (Fig. 1.11). Knees with ACL ruptures demonstrate an increase in medial and lateral compartment translation as the center of rotation shifts from inside the knee joint to outside the medial compartment. The medial ligamentous structures influence the new center of rotation, and therefore, a combined injury to these structures results in the center of rotation shifting far medially, causing a large anterior subluxation of both compartments. These knees require surgical restoration of severely injured medial and lateral ligament structures in addition to the ACL to restore knee stability.

The ACL and posterior cruciate ligament (PCL) 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.

Li et al. [49] reported that, in the lateral compartment in an uninjured knee, the contact region of the femur moves in a posterior direction on the tibial plateau during squatting (from 0° to 90° of flexion). Very little displacement occurs in the medial compartment of the femur relative to the tibia. Logan and associates [52] measured the translation of the lateral and medial compartments in intact and ACL-deficient knees during a Lachman test in a vertically oriented open-access magnetic resonance imaging (MRI) scanner. The ACL-deficient knees had significantly greater mean anterior tibial translation in both compartments, with the lateral side demonstrating greater translation than the medial side. The mean anterior tibial translation was significantly greater in the ACL-deficient knee compared to the intact knee in the medial compartment (8.2 ± 1.9 and 2.5 ± 1.7 mm, respectively, $P < 0.004$) and in the lateral compartment (14.1 ± 3.6 and 4.7 ± 2.3 mm, respectively, $P < 0.0002$).

Logan et al. [51] measured tibiofemoral motion in both compartments during a weight-bearing squat in an open access MRI scanner in ten patients who had unilateral ACL ruptures. There was a significant increase in the posterior translation of the femur on the tibia in the lateral compartment in the ACL-deficient knees compared to the intact knees throughout the arc of motion ($P < 0.001$). No difference was found between knees in medial compartment translation. The authors concluded that the change in kinematics caused greater internal tibial rotation during knee flexion, which may facilitate giving way during activity. Other changes in knee kinematics and kinetics with loss of ACL function are described in Chap. 2. The reader is referred to other references for a more extensive discussion on ACL function [69, 70].

One study compared male and female cadaveric knees to determine if gender differences existed in ACL structural and material properties [19]. 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 to 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.

Critical Points

- ACL primary restraint anterior tibial translation, provides 85–87 % total restraining force.
- ACL failure load 2,160 ± 157 N, stiffness 242 ± 28 N/mm.
- Limits coupled motions of internal tibial rotation and anterior tibial translation.
- Loss of ACL: increase in medial and lateral compartment translation as center of rotation shifts to outside the medial compartment.
- ACL and PCL are secondary restraints to medial and lateral joint opening, become primary restraints when collateral ligaments and capsules are ruptured.
- Female ACL appears to have lower mechanical properties than male ACL.

Common ACL Injury Mechanisms

Current Proposed Mechanisms

Knee joint stability during weight-bearing activities is influenced by the muscles, ligaments, and bony geometry which act together to resist potentially dangerous forces and external adduction moments (Fig. 1.12). At least two-thirds of ACL tears occur during noncontact situations while an athlete is cutting, pivoting, accelerating, decelerating, or landing from a jump [13, 15, 84]. Common injury circumstances have been described for both men and women, including perturbation of

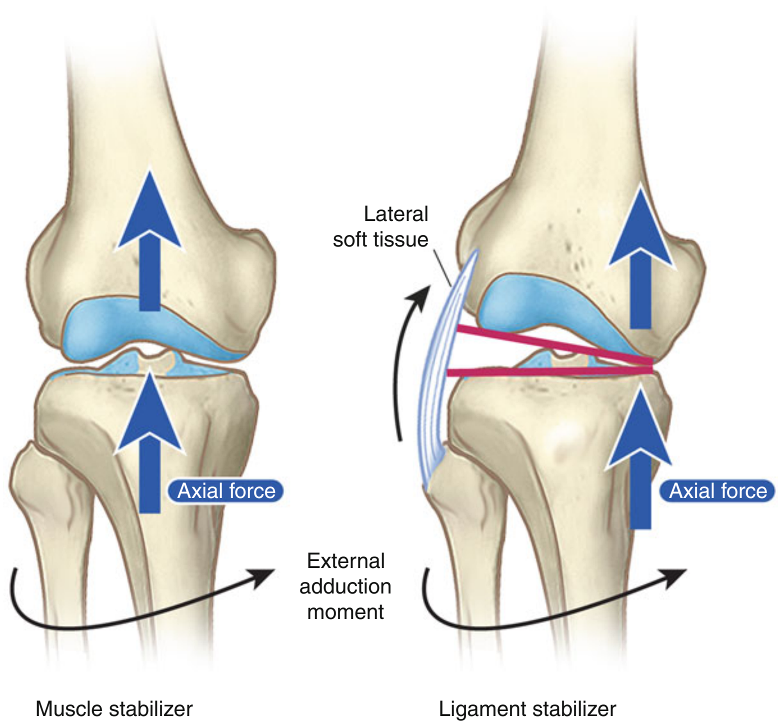


Fig. 1.12 *Left*, knee joint stability is influenced by the muscles, ligaments, and bony geometry, which act together to resist external adduction moments that are incurred during weight-bearing activities. *Right*, an abnormally high adduction moment may result in laxity of the lateral soft tissues 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 with permission from Barber-Westin and Noyes [8])

the athlete from an opponent, reported in ≥90 % of injuries in several studies [16, 42, 45, 74]. 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 producing ACL injury have been studied over the past two decades. These include [36]:

1. Anterior shear force, arising from large quadriceps contractions that occur with low knee flexion angles and lack of hamstrings muscle activation [5, 11, 12, 24, 27, 32, 48, 57]
2. Axial compression loads [47, 61]
3. Hyperextension [15, 56]
4. Valgus collapse at the knee joint [16, 45, 59, 85]
5. Internal tibial rotation [27, 58]
6. Combinations of #1–5

Markolf et al. [57] 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 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 laboratory study.

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. Debate exists regarding which of these neuromuscular mechanics are present at the time of the injury and which may occur just following the injury. Olsen and associates [74], in the first study to use videotape analysis of sequences of ACL injuries, 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. [35] in 2010 proposed a framework for establishing the viability of a noncontact ACL injury mechanism that included nine 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 does 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, excessive joint compression mechanisms, knee abduction moments (valgus), and tibial rotation. They believed that future studies needed to address a greater number of mechanisms in multiple plans and involving not only the knee joint but the hip and ankle joints as well.

Hashemi et al. [36] proposed a theory for a noncontact ACL injury mechanism comprised of four conditions: delayed or slow co-activation of quadriceps and hamstrings muscles, dynamic ground reaction force applied while the knee is near full extension, a shallow medial tibial plateau and steep posterior tibial slope, and a stiff landing due to incompatible hip and knee flexion angles. Experimental validation of this model is required.

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 [24, 48, 81] 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. [24] 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 4,500 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 three other knees. Fleming et al. [28] 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 [54, 62, 65] but has a marked functional dependence on the angle of knee flexion and degrees of external tibial rotation (Fig. 1.13). 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 [72, 75].

Pollard et al. [79] 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 to athletes who landed with greater hip and knee flexion (see also

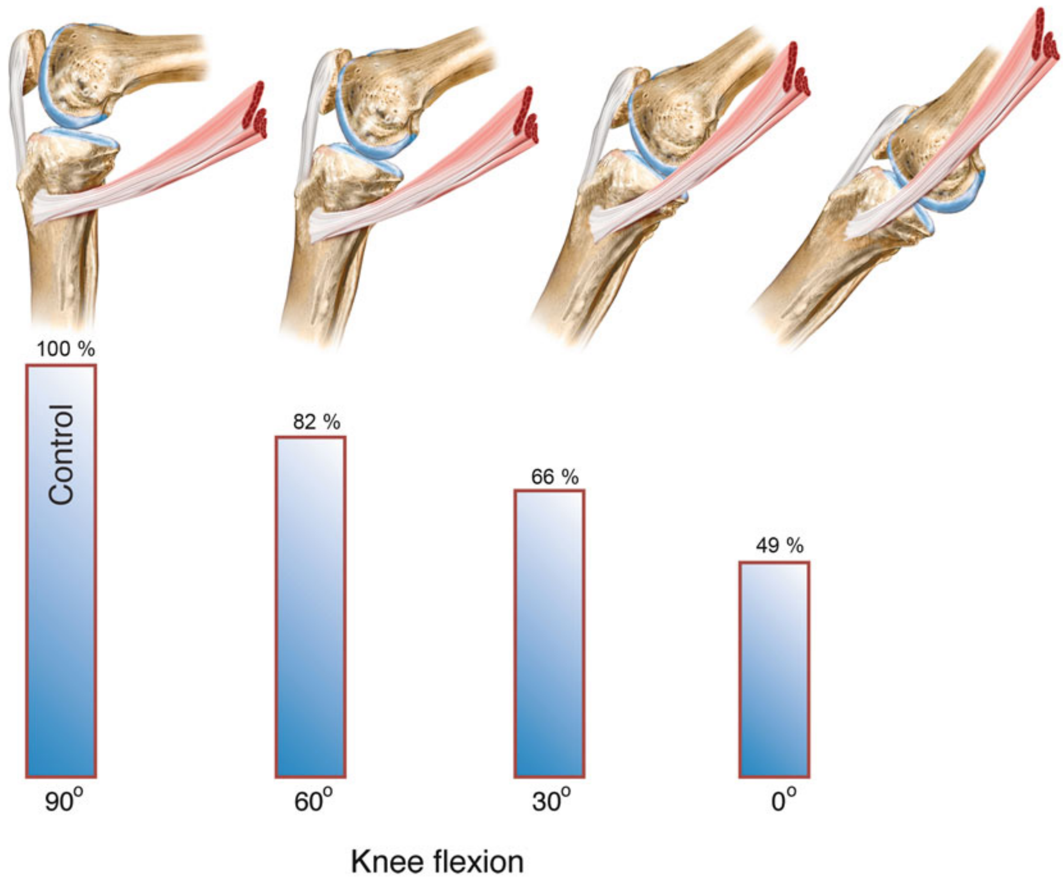


Fig. 1.13 Pes anserine (sartorius, gracilis, semitendinosus muscles) flexion forces. Stick figures show that knee extension yields a decrease in insertion course angles with respect to the tibia. Resulting loss in mechanical advantage is indicated by reduced flexion forces with extension ($P < 0.05$) (Reprinted with permission from Barber-Westin and Noyes [7])

Chap. 10). 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. [22] measured hamstring and quadriceps muscle activation and knee flexion angles during eccentric motion of sidestep cutting, crosscutting, 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 midstance. The peak quadriceps muscle activation occurred between 39° (stopping) and 53° (crosscutting) 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 % (crosscutting) 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 crosscutting). The authors concluded that the 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.

Video Analysis of ACL Injuries

Koga and associates [42] analyzed ten ACL injury sequences from female handball and basketball players. The video sequences were quantified using a computerized 3-dimensional analysis technique that replicated the lower limb and knee joint motions that occurred during the injuries. 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 initial foot contact before the injury, 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°). The authors noted 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°). 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 from initial foot contact.

Boden et al. [16] used videotapes of noncontact ACL injuries to conduct an analysis of the position of the hip and ankle in eight female and four male athletes. 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 to a control group analyzed during similar potential injury-type 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. The authors reported few differences in the injury mechanics between male and female athletes.

Krosshaug and associates [45] 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. Approximately one-half of the players were pushed or collided with another player just before the injury occurred, which may have altered the normal movement patterns of the subjects. 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 [44].

Olsen et al. [74] 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 were noted. The foot was firmly planted on the handball court and was outside of the knee 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. These authors also reported that 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.

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 [42, 45]. 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 broadcasts 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 [45]. The lack of control subjects performing similar athletic maneuvers without sustaining an ACL injury is another problem, as 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.

The authors 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, the authors 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 [68, 84]. 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 common
- 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 knee, 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.

The Gender Disparity in ACL Injury Rates

A study from the authors' center [50] published in 1994 was one of the first to report the gender disparity in ACL injury rates in soccer players using player-hours (or exposures) to calculate injury rates. A total of 300 indoor soccer games encompassing 2,700 player-hours were monitored for injuries. Although the overall injury rate was similar for female and male players, when analyzed just for serious knee ligament injuries, females were found to have nearly six times the rate of male players ($P<0.01$). The following year, Arendt and Dick [4] presented data from the National Collegiate Athletic Association (NCAA) of injuries sustained by soccer and basketball players using exposure rates over a 5-year period (1989–1993). Exposure was defined as one athlete participating in one practice or game. The ACL injury rate in females was more than double that of males in soccer (0.31 and 0.13 per 1,000 athlete-exposures, respectively, $P<0.05$) and four times that of males in basketball (0.29 and 0.07 per 1,000 athlete-exposures, respectively, $P<0.05$). In both sports, women were three times more likely to sustain this injury through noncontact mechanisms. Women were also more likely than men to undergo surgery for ACL tears in soccer (0.21 and 0.08 per 1,000 athlete-exposures, respectively) and basketball (0.23 and 0.04 per 1,000 athlete-exposures, respectively).

Messina and associates [60] followed athletes from 100 public high schools in the state of Texas over a single basketball season. There was no significant difference between genders in the overall rate of injuries per player exposure hours (3.2 injuries for boys and 3.6 injuries for girls per 1,000 player-hours). However, female players had nearly four times the incidence of ACL injuries than male players. The risk of injury during a game was significantly higher than during practice for both boys and girls (9.4 and 8 times higher, respectively, $P<0.0001$).

Gwinn et al. [33] evaluated the incidence of ACL tears in midshipmen at the United States Navel Academy over a 6-year period from 1991 to 1997. Women had a 4-fold increase in this injury compared to men in intercollegiate level soccer, basketball, and rugby collectively (0.511 and 0.129 per 1,000 athlete-exposures, respectively, $P=0.006$). In addition, women had nearly 11 times the incidence of ACL ruptures as men during obstacle course running (6.154 and 0.567 per 1,000 athlete-exposures, $P=0.004$). Overall per year, women midshipman had a relative injury risk of 2.44 compared with men ($P=0.0001$).

Table 1.1 ACL injury rates in female athletes for games and practices combined in the National Collegiate Athletic Association, 1988–1989 to 2003–2004 [39]

Sport	Injury rate per 1,000 athlete-exposures	95 % confidence interval
Gymnastics	0.33	0.28–0.39
Soccer	0.28	0.26–0.31
Basketball	0.23	0.21–0.25
Lacrosse	0.17	0.14–0.20
Volleyball	0.09	0.07–0.10
Softball	0.08	0.06–0.09
Field hockey	0.07	0.05–0.09

Mountcastle et al. [64] 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 to men in gymnastics (0.24 and 0.04 per 1,000 exposures, $P=0.001$) and the military indoor obstacle course test (0.94 and 0.25 per 1,000 exposures, $P=0.02$). 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.

Agel and associates [1] reviewed 13 years of NCAA injury data (1990–2002) from 6,176 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 ($P<0.01$). Hootman et al. [39] summarized 16 years of NCAA data in 15 different sports, assessing over one million exposures (defined as one athlete participating in one practice or game). Women's gymnastics had the highest ACL injury rate (0.33 per 1,000 athlete exposures, Table 1.1), which was similar to men's spring football. Female basketball players had a 3-fold higher ACL injury incidence compared to male players (0.23 vs. 0.07 per 1,000 athlete exposures), as did female soccer players compared to their male counterparts (0.28 vs. 0.09 per 1,000 athlete exposures). The majority of ACL injuries (88 %)

Table 1.2 Meta-analysis ACL injury rates for male and female athletes [80][a]

		Female athletes			Male athletes		
Sport	Level	No. exposures	No. ACL tears	Incidence rate (per 1,000 exposures)	No. exposures	No. ACL tears	Incidence rate (per 1,000 exposures)
Basketball	Professional	45,036	9	0.20	70,185	15	0.21
	Collegiate	7,119,962	2,049	0.29	8,300,072	645	0.08
	High School	233,538	27	0.10	169,885	4	0.02
Soccer	Collegiate	4,873,287	1,570	0.32	6,881,281	842	0.12
	High school	155,822	70	0.45	NA	NA	NA
Handball	Elite	40,799	23	0.56	43,891	5	0.11
	Adult recreational	5,815	5	0.86	20,462	5	0.24
Lacrosse	Collegiate	799,611	146	0.18	984,292	169	0.17
Rugby	Collegiate	66,771	24	0.36	22,788	4	0.18
Wrestling	Collegiate	1,306	1	0.77	10.582	2	0.19

[a]Females had significantly higher mean incidence rates than males in basketball, soccer, and handball ($P < 0.0001$)

resulted in 10 or more days of lost playing time. The rate of ACL injuries increased 1.3 % on average per year over the 16-year period.

In the only study to date that evaluated the effect of race on ACL injury rates in women, Trojian and Collins [90] assessed data over five seasons of play from the Women's National Basketball Association. White European American women had a higher ACL injury rate (0.45 per 1,000 athlete exposures) compared to black (0.04 per 1,000 athlete exposures) and non-white European-American players (0.07 per 1,000 athlete exposures). However, there were only 9 ACL injuries in 45,036 exposures which limit the study's conclusions.

Prodromos and associates [80] conducted a meta-analysis entailing 33 articles to test the hypothesis that the incidence of ACL tears would show variation by sport, gender (Table 1.2), 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 [38, 55, 76, 78, 87] showed that neuromuscular training was effective in significantly reducing the ACL tear rates in soccer and basketball.

Critical Points

- Indoor soccer: females 6× rate of males
- NCAA 1989–1993: females >2× males in soccer, 4× males in basketball.
- High school basketball: females 4× males
- US Naval Academy 6 years: women 4× men soccer, basketball, and rugby collectively; 11× men obstacle course
- NCAA 1990–2002: female soccer and basketball players significantly greater incidence than males
- Meta-analysis 33 articles: ACL injury rate for females 3× males in basketball and soccer, 5× males in handball

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 III. The question of what places female athletes in certain sports at a higher risk for sustaining a serious knee ligament injury than male athletes represents an ongoing dilemma not yet answered. The major risk categories that have been the focus of research to date include genetics, environmental, anatomical, hormonal, and neuromuscular/biomechanical. Some of the problems with prior studies include small sample sizes of each gender, data collected on only one risk category, or examination of neuromuscular characteristics in a controlled laboratory environment using preplanned tasks. Future investigations should study larger sample sizes of athletes, analyze factors from all of the major risk categories in a multivariate model, and assess neuromuscular indices during reactive (unplanned) tasks under realistic sports conditions [9].

Elliot et al. [25] proposed other potential risk factors which should be explored in future studies. These included lifestyle habits and psychosocial influences of female athletes such as fatigue from chronic sleep deprivation, poor nutrition and eating disorders, substance use and abuse, overtraining, stress, and depression. These authors recommended that injury prevention training programs should include education on these factors as well as neuromuscular retraining and conditioning.

The impact of ACL injuries, including the high risk of premature osteoarthritis, is discussed in Part II. 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 [26, 30, 53]. 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 arthritis [14]. Authors have reported that 10–30 % 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 which failed to include advanced neuromuscular retraining [10, 82, 83].

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. Even so, the authors believe that neuromuscular retraining (as described in Part IV) should become widespread to include all female athletes involved in high-risk sports such as basketball and soccer. Research has shown that comprehensive training programs can effectively "reprogram" the neuromuscular system to avoid potentially dangerous body mechanics and positions (Fig. 1.14). Certain studies have proposed that these alterations in neuromuscular indices and movement patterns may reduce the incidence of noncontact ACL ruptures [38, 55].

Fig. 1.14 Video drop-jump test before (**a**) and after (**b**) neuromuscular retraining

Fig. 1.14 (continued)

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.
- Alterations in neuromuscular indices and movement patterns have resulted in a reduction in the incidence of noncontact ACL ruptures.

References

1. Agel J, Arendt EA, Bershadsky B (2005) Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. Am J Sports Med 33(4):524–530
2. Ait Si Selmi T, Fithian D, Neyret P (2006) The evolution of osteoarthritis in 103 patients with ACL reconstruction at 17 years follow-up. Knee 13(5):353–358
3. Amis A, Dawkins G (1991) Functional anatomy of the anterior cruciate ligament. Fibre bundle actions related to ligament replacements and injuries. J Bone Joint Surg 73B(2):260–267
4. Arendt E, Dick R (1995) Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. Am J Sports Med 23(6):694–701
5. Arms SW, Pope MH, Johnson RJ et al (1984) The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. Am J Sports Med 12(1):8–18
6. Baer GS, Harner CD (2007) Clinical outcomes of allograft versus autograft in anterior cruciate ligament reconstruction. Clin Sports Med 26(4):661–681
7. Barber-Westin SD, Noyes FR (2009) Risk factors for anterior cruciate ligament injuries in the female athlete. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 359–378
8. Barber-Westin SD, Noyes FR (2009) Lower limb neuromuscular control and strength in prepubescent and adolescent male and female athletes. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 379–403
9. Barber-Westin SD, Noyes FR, Smith ST et al (2009) Reducing the risk of noncontact anterior cruciate ligament injuries in the female athlete. Phys Sportsmed 37(3):49–61
10. Barber-Westin SD, Noyes FR (2011) Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. Phys Sportsmed 39(3):100–110
11. Berns GS, Hull ML, Patterson HA (1992) Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. J Orthop Res 10(2):167–176
12. Beynnon BD, Fleming BC, Johnson RJ et al (1995) Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. Am J Sports Med 23(1):24–34
13. Beynnon BD, Johnson RJ, Abate JA et al (2005) Treatment of anterior cruciate ligament injuries, part I. Am J Sports Med 33(10):1579–1602
14. Beynnon BD, Uh BS, Johnson RJ (2005) Rehabilitation after anterior cruciate ligament reconstruction. A prospective, randomized, double-blind comparison of programs administered over 2 different time periods. Am J Sports Med 33(3):347–359
15. Boden BP, Dean GS, Feagin JA Jr et al (2000) Mechanisms of anterior cruciate ligament injury. Orthopedics 23(6):573–578
16. Boden BP, Torg JS, Knowles SB et al (2009) Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. Am J Sports Med 37(2):252–259
17. Brand E, Nyland J (2009) Patient outcomes following anterior cruciate ligament reconstruction: the influence of psychological factors. Orthopedics 32(5):335

18. Butler DL, Noyes FR, Grood ES (1980) Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. J Bone Joint Surg Am 62(2):259–270
19. Chandrashekar N, Mansouri H, Slauterbeck J et al (2006) Sex-based differences in the tensile properties of the human anterior cruciate ligament. J Biomech 39(16):2943–2950
20. Clayton RA, Court-Brown CM (2008) The epidemiology of musculoskeletal tendinous and ligamentous injuries. Injury 39(12):1338–1344
21. Clemente CD (2007) Anatomy: a regional atlas of the human body, 5th edn. Lippincott, Williams and Wilkins, Baltimore
22. Colby S, Francisco A, Yu B et al (2000) Electromyographic and kinematic analysis of cutting maneuvers. Implications for anterior cruciate ligament injury. Am J Sports Med 28(2):234–240
23. Colombet P, Robinson J, Christel P et al (2006) Morphology of anterior cruciate ligament attachments for anatomic reconstruction: a cadaveric dissection and radiographic study. Arthroscopy 22(9):984–992
24. DeMorat G, Weinhold P, Blackburn T et al (2004) Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. Am J Sports Med 32(2):477–483
25. Elliot DL, Goldberg L, Kuehl KS (2010) Young women's anterior cruciate ligament injuries: an expanded model and prevention paradigm. Sports Med 40(5): 367–376
26. Fithian DC, Paxton LW, Goltz DH (2002) Fate of the anterior cruciate ligament-injured knee. Orthop Clin North Am 33(4):621–636, v
27. Fleming BC, Renstrom PA, Beynnon BD et al (2001) The effect of weightbearing and external loading on anterior cruciate ligament strain. J Biomech 34(2): 163–170
28. Fleming BC, Renstrom PA, Ohlen G et al (2001) The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. J Orthop Res 19(6):1178–1184
29. Frobell RB, Lohmander LS, Roos HP (2007) Acute rotational trauma to the knee: poor agreement between clinical assessment and magnetic resonance imaging findings. Scand J Med Sci Sports 17(2):109–114
30. Graham GP, Fairclough JA (1988) Early osteoarthritis in young sportsmen with severe anterolateral instability of the knee. Injury 19(4):247–248
31. Granan LP, Bahr R, Steindal K et al (2008) Development of a national cruciate ligament surgery registry: the Norwegian National Knee Ligament Registry. Am J Sports Med 36(2):308–315
32. Grood ES, Suntay WJ, Noyes FR et al (1984) Biomechanics of the knee-extension exercise. Effect of cutting the anterior cruciate ligament. J Bone Joint Surg Am 66(5):725–734
33. Gwinn DE, Wilckens JH, McDevitt ER et al (2000) The relative incidence of anterior cruciate ligament injury in men and women at the United States Naval Academy. Am J Sports Med 28(1):98–102
34. Hanypsiak BT, Spindler KP, Rothrock CR et al (2008) Twelve-year follow-up on anterior cruciate ligament reconstruction: long-term outcomes of prospectively studied osseous and articular injuries. Am J Sports Med 36(4):671–677
35. Hashemi J, Breighner R, Chandrashekar N et al (2010) Letter to the editor: a framework for assessing the viability of proposed anterior cruciate ligament injury mechanisms. Am J Sports Med 38(7):NP3–NP7
36. Hashemi J, Breighner R, Chandrashekar N et al (2011) Hip extension, knee flexion paradox: a new mechanism for non-contact ACL injury. J Biomech 44(4): 577–585
37. Hefzy MS, Grood ES, Noyes FR (1989) Factors affecting the region of most isometric femoral attachments. Part II: the anterior cruciate ligament. Am J Sports Med 17(2):208–216
38. Hewett TE, Lindenfeld TN, Riccobene JV et al (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27(6):699–706
39. Hootman JM, Dick R, Agel J (2007) Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. J Athl Train 42(2):311–319
40. Hutchinson MR, Ash SA (2003) Resident's ridge: assessing the cortical thickness of the lateral wall and roof of the intercondylar notch. Arthroscopy 19(9): 931–935
41. Kim S, Bosque J, Meehan JP et al (2011) Increase in outpatient knee arthroscopy in the United States: a comparison of National Surveys of Ambulatory Surgery, 1996 and 2006. J Bone Joint Surg Am 93(11): 994–1000
42. Koga H, Nakamae A, Shima Y et al (2010) Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. Am J Sports Med 38(11):2218–2225
43. Kostogiannis I, Ageberg E, Neuman P et al (2007) Activity level and subjective knee function 15 years after anterior cruciate ligament injury: a prospective, longitudinal study of nonreconstructed patients. Am J Sports Med 35(7):1135–1143
44. Krosshaug T, Nakamae A, Boden B et al (2007) Estimating 3D joint kinematics from video sequences of running and cutting maneuvers – assessing the accuracy of simple visual inspection. Gait Posture 26(3):378–385
45. Krosshaug T, Nakamae A, Boden BP et al (2007) Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. Am J Sports Med 35(3):359–367
46. Langford JL, Webster KE, Feller JA (2009) A prospective longitudinal study to assess psychological changes following anterior cruciate ligament reconstruction surgery. Br J Sports Med 43(5):377–378
47. Li G, Rudy TW, Allen C et al (1998) Effect of combined axial compressive and anterior tibial loads on in

situ forces in the anterior cruciate ligament: a porcine study. J Orthop Res 16(1):122–127
48. Li G, Rudy TW, Sakane M et al (1999) The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. J Biomech 32(4):395–400
49. Li G, DeFrate LE, Park SE et al (2005) In vivo articular cartilage contact kinematics of the knee: an investigation using dual-orthogonal fluoroscopy and magnetic resonance image-based computer models. Am J Sports Med 33(1):102–107
50. Lindenfeld TN, Schmitt DJ, Hendy MP et al (1994) Incidence of injury in indoor soccer. Am J Sports Med 22(3):364–371
51. Logan M, Dunstan E, Robinson J et al (2004) Tibiofemoral kinematics of the anterior cruciate ligament (ACL)-deficient weightbearing, living knee employing vertical access open “interventional” multiple resonance imaging. Am J Sports Med 32(3):720–726
52. Logan MC, Williams A, Lavelle J et al (2004) What really happens during the Lachman test? A dynamic MRI analysis of tibiofemoral motion. Am J Sports Med 32(2):369–375
53. Lohmander LS, Englund PM, Dahl LL et al (2007) The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. Am J Sports Med 35(10):1756–1769
54. MacWilliams BA, Wilson DR, DesJardins JD et al (1999) Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. J Orthop Res 17(6):817–822
55. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010
56. Markolf KL, Gorek JF, Kabo JM et al (1990) Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. J Bone Joint Surg Am 72(4): 557–567
57. Markolf KL, Burchfield DM, Shapiro MM et al (1995) Combined knee loading states that generate high anterior cruciate ligament forces. J Orthop Res 13(6): 930–935
58. Markolf KL, O’Neill G, Jackson SR et al (2004) Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. Am J Sports Med 32(5):1144–1149
59. McLean SG, Huang X, van den Bogert AJ (2005) Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. Clin Biomech (Bristol, Avon) 20(8):863–870
60. Messina DF, Farney WC, DeLee JC (1999) The incidence of injury in Texas high school basketball. A prospective study among male and female athletes. Am J Sports Med 27(3):294–299
61. Meyer EG, Haut RC (2005) Excessive compression of the human tibio-femoral joint causes ACL rupture. J Biomech 38(11):2311–2316
62. More RC, Karras BT, Neiman F et al (1993) Hamstrings-an anterior cruciate ligament protagonist: an in vitro study. Am J Sports Med 21:231–237
63. Morrey MA, Stuart MJ, Smith AM et al (1999) A longitudinal examination of athletes’ emotional and cognitive responses to anterior cruciate ligament injury. Clin J Sport Med 9(2):63–69
64. Mountcastle SB, Posner M, Kragh JF Jr et al (2007) Gender differences in anterior cruciate ligament injury vary with activity: epidemiology of anterior cruciate ligament injuries in a young, athletic population. Am J Sports Med 35(10):1635–1642
65. Noyes FR, Sonstegard DA (1973) Biomechanical function of the pes anserinus at the knee and the effect of its transplantation. J Bone Joint Surg Am 55(6):1225–1241
66. Noyes FR, Grood ES, Butler DL et al (1980) Clinical laxity tests and functional stability of the knee: biomechanical concepts. Clin Orthop 146:84–89
67. Noyes FR, Grood ES (1987) Classification of ligament injuries: why an anterolateral laxity or anteromedial laxity is not a diagnostic entity. Instr Course Lect 36:185–200
68. 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
69. Noyes FR, Barber-Westin SD (2009) Anterior cruciate ligament primary and revision reconstruction: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR (ed) Noyes’ knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 140–228
70. Noyes FR, Grood ES (2009) Knee ligament function and failure. In: Noyes FR (ed) Noyes’ knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 89–113
71. Noyes FR, Grood ES (2009) The scientific basis for examination and classification of knee ligament injuries. In: Noyes FR (ed) Noyes’ knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 47–88
72. O’Connor JJ (1993) Can muscle co-contraction protect knee ligaments after injury or repair? J Bone Joint Surg Br 75(1):41–48
73. Ochiai S, Hagino T, Tonotsuka H et al (2010) Health-related quality of life in patients with an anterior cruciate ligament injury. Arch Orthop Trauma Surg 130(3):397–399
74. Olsen OE, Myklebust G, Engebretsen L et al (2004) Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am J Sports Med 32(4):1002–1012
75. Pandy MG, Shelburne KB (1997) Dependence of cruciate-ligament loading on muscle forces and external load. J Biomech 30(10):1015–1024

76. Petersen W, Braun C, Bock W et al (2005) A controlled prospective case control study of a prevention training program in female team handball players: the German experience. Arch Orthop Trauma Surg 125(9):614–621
77. Petersen W, Zantop T (2007) Anatomy of the anterior cruciate ligament with regard to its two bundles. Clin Orthop Relat Res 454:35–47
78. Pfeiffer RP, Shea KG, Roberts D et al (2006) Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. J Bone Joint Surg Am 88(8):1769–1774
79. Pollard CD, Sigward SM, Powers CM (2010) Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. Clin Biomech (Bristol, Avon) 25(2):142–146
80. Prodromos CC, Han Y, Rogowski J et al (2007) A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. Arthroscopy 23(12): 1320.e6–1325.e6
81. Renstrom P, Arms SW, Stanwyck TS et al (1986) Strain within the anterior cruciate ligament during hamstring and quadriceps activity. Am J Sports Med 14(1):83–87
82. Salmon L, Hui C, Roe J et al (2010) Incidence and risk factors for reinjury 15 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Paper presented at the annual meeting of the American Academy of Orthopaedic Surgeons, New Orleans, LA, 12 March 2010
83. Salmon LJ, Russell VJ, Refshauge K et al (2006) Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. Am J Sports Med 34(5):721–732
84. Shimokochi Y, Shultz SJ (2008) Mechanisms of noncontact anterior cruciate ligament injury. J Athl Train 43(4):396–408
85. Shin CS, Chaudhari AM, Andriacchi TP (2009) The effect of isolated valgus moments on ACL strain during single-leg landing: a simulation study. J Biomech 42(3):280–285
86. Sidles JA, Larson RV, Garbini JL et al (1988) Ligament length relationship in the moving knee. J Orthop Res 6(4):593–610
87. Soderman K, Werner S, Pietila T et al (2000) Balance board training: prevention of traumatic injuries of the lower extremities in female soccer players? A prospective randomized intervention study. Knee Surg Sports Traumatol Arthrosc 8(6):356–363
88. Standring S (2005) Gray's anatomy: the anatomical basis of clinical practice. Churchill Livingstone, New York
89. Strickland JP, Fester EW, Noyes FR (2009) Lateral, posterior, and cruciate knee anatomy. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 20–43
90. Trojian TH, Collins S (2006) The anterior cruciate ligament tear rate varies by race in professional Women's basketball. Am J Sports Med 34(6): 895–898
91. Udry E, Donald Shelbourne K, Gray T (2003) Psychological readiness for anterior cruciate ligament surgery: describing and comparing the adolescent and adult experiences. J Athl Train 38(2):167–171
92. Woo SL-Y, Hollis JM, Adams DJ et al (1991) Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. Am J Sports Med 19(3):217–225
93. Yu B, Kirkendall DT, Taft TN et al (2002) Lower extremity motor control-related and other risk factors for noncontact anterior cruciate ligament injuries. Instr Course Lect 51:315–324

Part II

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

Consequences of Complete ACL Ruptures

2

Sue D. Barber-Westin and Frank R. Noyes

Contents

S.D. Barber-Westin, B.S (✉)
Cincinnati Sportsmedicine Research and Education Foundation,
10663 Montgomery Road, Cincinnati, Ohio 45242, USA
e-mail: sbwestin@csmref.org

F.R. Noyes, M.D.
Cincinnati Sportsmedicine and Orthopaedic Center,
10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Cincinnati Sportsmedicine Research and Education Foundation,
10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Introduction

There are few long-term prospective studies (with a minimum of 10 years of follow-up) describing the natural history of the anterior cruciate ligament (ACL) deficient knee [3, 47, 87, 108, 116–118]. It is important to define complete from partial ACL-deficiency and to realize that some studies combine patients with these diagnoses into one cohort, making conclusions difficult on the effects of a completely deficient and 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 Documentations Committee (IKDC) ligament examination grade of C (abnormal) or D (severely abnormal) also identifies a complete ACL tear. In contrast, patients with <5 mm of increased

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_2, © Springer-Verlag Berlin Heidelberg 2012

Fig. 2.1 Fully positive Lachman test (Reprinted with permission from Noyes and Barber-Westin [126])

anterior tibial translation or a grade 1 pivot-shift test are considered to have a partial ACL tear with some residual function remaining, or may have an intact ACL with physiologic laxity. 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, arthrometer testing, or a combination of these measures.

Studies vary regarding the percentage of patients who sustain repeat giving-way episodes and meniscus injuries, or who have swelling, symptoms with athletic and daily activities, and alterations in muscle activation patterns and neuromuscular control. Even so, the general consensus is that a complete ACL rupture causes long-term problems in the knee joint, especially an early onset of osteoarthritis compared to the general population [49, 58, 97]. Roos et al. [136] reported that patients with chronic, untreated ACL ruptures showed radiologic signs of osteoarthritis (joint space narrowing) 10 years earlier than patients with intact ACLs and chronic meniscus tears that had not been surgically addressed. The study involved 564 patients with ACL tears and 401 patients with meniscus tears who presented with chronic symptoms for treatment. Lohmander et al. [96] 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. [121] reported that 44 % of 39 patients with chronic ACL ruptures of at least 5 years duration had moderate to severe osteoarthritic changes on X-rays.

A significant problem is that few patients sustain a truly isolated ACL tear, as 80–95 % have bone bruising; 60 %, meniscus tears; and 20 %, chondral injuries [15, 49, 169]. Further compounding the problem is the occurrence of subsequent meniscus tears that are reported in the majority of natural history studies [8, 16, 23, 26, 34, 35, 49, 58, 61, 78, 85, 117, 120, 121, 147, 160], along with chondral injuries and articular cartilage lesions that presumably result from further giving-way episodes [26, 35, 37, 46, 49, 58, 78, 92, 144, 149] or increased catabolic activity [27]. Levy and Meier [92] reported that the frequency of articular cartilage damage in chronic ACL-deficient knees was 79 % overall, with increases from 40 % at 1 year, 60 % at 5 years, and >80 % 10 years following the injury.

Few studies have used arthroscopy or advanced magnetic resonance imaging (MRI) technology such as T2 mapping in knees with chronic ACL ruptures to ascertain the status of the articular cartilage years after the original injury [29]. There is substantial evidence that knees with ACL-deficiency that undergo meniscectomy (Fig. 2.2) have an increased risk of developing early arthritis compared to those that do not sustain meniscus damage (see also Chap. 3) [35, 47, 117, 135,

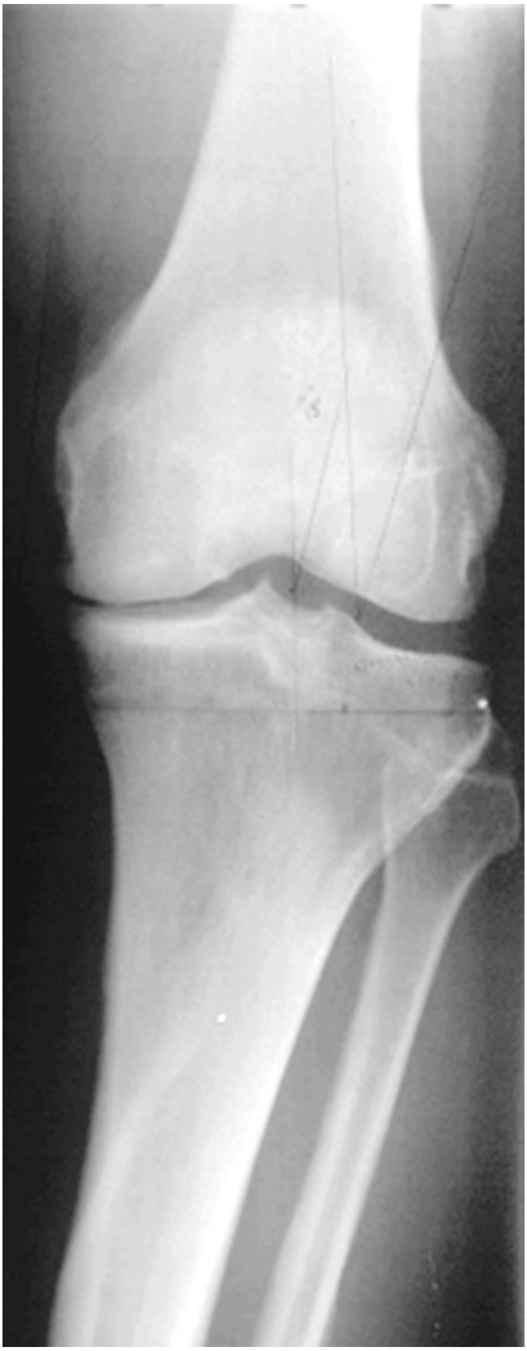


Fig. 2.2 Anteroposterior radiograph of a chronic ACL-deficient knee that underwent a medial meniscectomy. The patient presented to our center 7 years later with medial tibiofemoral joint pain and required a high tibial osteotomy for varus malalignment

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.

144, 147]. In addition, knees with combined ACL tears and meniscus tears may exhibit a higher expression of catabolic markers than those with isolated meniscus tears, which may lead to a higher risk for the development of osteoarthritis [27].

Consequences of ACL-Deficiency

Alterations in Knee Kinematics

There are different theories regarding the causes of early arthritis in ACL-deficient knees even in the absence of meniscectomy or marked chondral injury. These include altered knee kinematics, quadriceps weakness, and abnormal gait patterns that increase or alter joint loads and contact pressures. Beynnon et al. [21] hypothesized that an increase in anterior tibial translation over 3 mm may lead to adverse degenerative changes over time. Chaudhari and associates [31] believed that changes in tibiofemoral knee motion following ACL injury during walking resulted in increased loading in areas of the articular cartilage not accustomed to such loads, as well as reduced loading in areas conditioned to receive large loads. These alterations were speculated to shift contact pressure distributions and induce cartilage deterioration (Fig. 2.3). Andriacchi and associates [11] used a finite element model from three-dimensional cartilage volumes created from MRI to predict progression of osteoarthritis in normal and ACL-deficient knees. A more rapid rate of cartilage thinning was

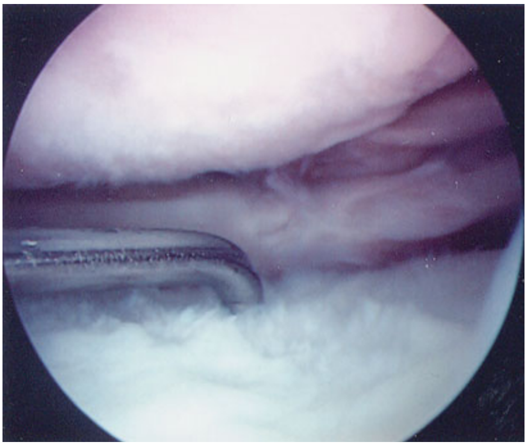


Fig. 2.3 A 21-year-old patient who underwent a lateral meniscectomy 2 years prior to presentation to our center. Diffuse articular cartilage damage is visible on both the lateral femoral condyle and lateral tibial plateau (Reprinted with permission from Noyes and Barber-Westin [125])

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 and associates [95] 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 to 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 to 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 osteoarthritis 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 [99, 135].

Bone Loss, Osseous Deficits

Nyland et al. [127] 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 [18, 64].

Bayar and associates [18] assessed BMD in 32 males 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.

Chronic Quadriceps Weakness

Chronic quadriceps weakness has been postulated as a risk factor for posttraumatic osteoarthritis in the ACL-deficient knee [130, 151]. 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 several investigations in chronic ACL-deficient patients [56, 88, 98, 106, 122, 148, 156, 157, 165, 166]. It is important to determine the effect of activity level and symptoms in these studies, as this persistent problem may be due to inactivity. For instance, Wojtys and Huston [165] reported that ACL-deficient subjects who had returned to competitive intercollegiate athletics without problems had significantly increased quadriceps and hamstring peak torque compared to patients who had symptoms and much lower activity levels ($P<0.05$).

Arthrogenic muscle inhibition (AMI) has been hypothesized by some investigators to cause acute and chronic quadriceps weakness in ACL-deficient knees [65, 130]. 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, thus resulting in chronic quadriceps weakness. The persistent muscle atrophy is postulated to be a factor in altered neuromuscular control during dynamic activities.

Chronic hamstring weakness does not appear to be as problematic in ACL-deficient knees as quadriceps problems [122, 148, 157, 165]. However, Tsepis et al. [157] 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 following their ACL injury. Patients with poor Lysholm scores had significantly lower average peak torque in the ACL-deficient knee compared to the opposite knee ($P<0.001$), whereas patients with Lysholm scores >84 points had equivalent strength bilaterally. Similar trends were documented by Wojtys and Huston [165] who reported that patients with low activity levels and symptoms had decreased

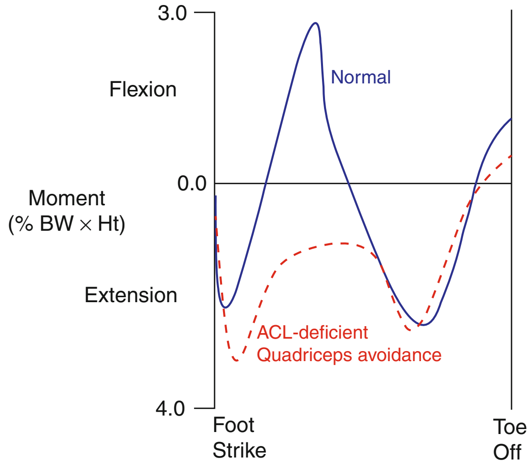


Fig. 2.4 The normal pattern of flexion-extension moment at the knee during the stance phase of gait (*blue line*) and the pattern of quadriceps avoidance as described by Berchuck et al. [20] in some ACL-deficient subjects

hamstring peak torque compared to those who had returned to competitive athletics. The increase in hamstring muscle activity typically noted during functional activities in ACL-deficient knees may be the reason for the smaller deficits measured, as discussed below.

Gait Abnormalities

Chronic ACL-deficiency produces marked alterations in gait during a variety of activities [7, 9–11, 20, 54, 123, 131, 161]. Long-term quadriceps weakness [78] frequently accompanies the gait abnormalities. For instance, during the loading phase of level walking, ACL-deficient subjects have significantly decreased external knee flexion moments and increased external knee extension moments compared to uninjured control subjects (Fig. 2.4) [137, 161]. 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 [123], 7 of 8 subjects >7 years post-injury in an investigation by Wexler et al. [161], and 12 of 16 (75 %) subjects in a study by Berchuck et al. [20]. Berchuck and associates [20] reported that the magnitude of the maximum moment that tended to flex the knee 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. Patel et al. [131] 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. Rudolph and associates [137] reported that ACL-deficient subjects had decreased jogging speed and stride length compared with healthy subjects.

Fuentes et al. [54] 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 to a control 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.

Wexler and associates [161] reported that changes in sagittal plane knee moments were more pronounced as the amount of time after the ACL injury increased. Patients underwent gait analysis testing either early (<2.5 years), intermediate (2.5–7.5 years), or late (>7.5 years) after their ACL injury. Adaptation to the injury over time was apparent, with a tendency for decreased knee flexion moments and increased knee extension moments. The authors concluded that this represented an attempt to decrease the abnormal anterior tibial translation by reducing the anterior pull of the quadriceps and increasing hamstrings activity.

Andriacchi et al. [12] reported that, during the swing phase of walking, ACL-deficient knees had reduced external rotation and anterior translation as the knee extended prior to heel strike. Andriacchi and Scanlan [13] summarized 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. Patients with ACL injuries demonstrated a rotational offset in the position of the tibia that was maintained during the stance phase of walking.

Changes in Muscle Activation Strategies During Functional Activities

Patients with ACL-deficient knees commonly demonstrate different lower extremity dynamic muscle activation patterns compared to noninjured 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 or phase of walking [32]. In the studies described below, the chronic ACL-deficient patients were tested ≥6 months from their injury, had completed rehabilitation, and returned to activities without further instability episodes.

Swanik et al. [152] studied electromyographic (EMG) activity during landing from a hop and knee perturbation in 12 females with ACL-deficient knees and 17 female control subjects. The patients had significantly increased muscle activity in the lateral hamstring before landing compared to the control group ($P = 0.05$), less hamstring muscle stiffness and flexibility, and greater hamstring peak torque ($P = 0.01$). There was no difference between groups in muscle activity on landing or in the single-leg hop test.

DeMont et al. [42] studied muscular activity before footstrike in six ACL-deficient female patients and six female control subjects during walking down an incline, running, hopping, and landing from a jump. The ACL-deficient subjects had EMG side-to-side differences not demonstrated by the controls. For instance, the patients had reduced lateral gastrocnemius activity on landing ($P<0.05$), increased vastus medialis oblique (VMO) and vastus lateralis activity during running ($P<0.05$), and decreased VMO activity during downhill walking ($P<0.05$). The authors concluded that different muscle activation strategies were used by the ACL-deficient subjects as a protective mechanism or accommodation for the ligament deficiency.

Ciccotti and associates [32] measured EMG activity during 7 functional activities in 8 ACL-deficient patients, 10 ACL-reconstructed patients, and 22 uninjured subjects. The ACL-deficient group had 23 statistically significant increases in EMG muscle activity during the various activities compared to the normal subjects and/or ACL-reconstructed patients. These included increased vastus lateralis activity during the loading response phase of walking, increased rectus femoris activity during preswing, increased biceps femoris muscle activity during terminal swing, and increased tibialis anterior muscle activity during terminal stance. Similar findings were reported during ramp and stair ascending and descending. During the early stance phase of running, the VMO and vastus lateralis muscle activity was lower than the uninjured subjects, which the authors attributed to as a possible quadriceps avoidance [20] mechanism. Significantly increased rectus femoris muscle activity was noted during middle swing, and increased tibialis anterior musculature was found at the end of stance.

Atypical muscle activation patterns in ACL-deficient knees were observed by Shiavi and associates [145] during fast walking. In a group of 20 patients, 85 % demonstrated at least 4 atypical patterns of reduced muscle activity during single-leg stance. Limbird et al. [94] also reported significant differences between 12 ACL-deficient patients and 15 control subjects during fast walking. The ACL-deficient patients had less activity in the quadriceps and gastrocnemius muscle groups and greater activity in the biceps femoris group during swing-to-stance phase transition. Compared to the control subjects, the vastus lateralis was more active in the ACL-deficient patients during early swing, and the hamstrings were less active during midstance and terminal stance.

Branch and associates [25] studied the effect of derotation braces on muscle activation strategies in 10 ACL-deficient patients and 5 control subjects during a side step cutting maneuver. The patients had increased lateral hamstring activity during swing phase while preparing to cut. During the cut/stance phase itself, the patients had greater medial hamstring activity, but decreased quadriceps and gastrocnemius activity compared to controls. Bracing did not alter EMG firing patterns.

Wojtys and Huston [165] evaluated 100 chronic ACL-deficient knees and 40 control subjects to determine if differences existed in lower extremity isokinetic strength and endurance, and muscular response and recruitment order in response to an anterior tibial translation force. Patients with ACL injuries initially used the quadriceps muscles to resist the anterior tibial translation force, whereas those with chronic injuries initially activated the hamstrings. All of the patients had slower muscle reaction times in response to the translation force compared to uninjured controls and their opposite limb. Even the highest-performing athletes (who were 18 months post-injury) could not obtain muscle response times equal to that of controls. The authors concluded that if the afferent arm of the protective reflex system was damaged, then normal neuromuscular function might not be achievable regardless of the program of rehabilitation.

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 [71, 139]. These include Ruffini endings, Pacinian corpuscles, and Golgi tendon organs [84]. 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 [19, 165].

The most common tests for proprioception are threshold for detection of passive motion (TDPM), active or passive reproduction of a standardized angular change in the knee, and joint position sense (JPS). There exists evidence that some patients may experience altered proprioception [1, 17, 36, 48, 52, 74] and balance control [2, 63, 69, 90, 110, 134, 170] following ACL injury. Control of posture and balance, either static or dynamic, is dependent on sensory information gained from proprioception and vestibular and visual systems. Impairment of any of these factors may affect postural control.

Adachi et al. [1] examined the remnants of ruptured ACLs in 29 knees removed arthroscopically. The mean interval from injury to surgery was 8 months (range, 2 months–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 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 ($R=-0.41$, $P=0.03$).

Friden et al. [52] detected significant differences in 16 patients in their ability to detect passive motion 1 and 2 months following ACL rupture between the injured and contralateral limbs ($P<0.05$). The differences were found with the knee close to full extension. Jerosch and Prymka [74] also found a bilateral deficit in joint position perception with reproduction of active and passive knee joint position. However, these deficits were found near the midrange of knee motion.

Katayama and associates [80] measured JPS in 32 chronic ACL-deficient knees and found significant differences between the injured and contralateral limbs (5.2° and 3.6°, respectively, $P<0.05$). Corrigan et al. [36] reported deficits in JPS and threshold for movement detection in a group of 20 chronic ACL-deficient subjects compared to controls. An association was found between these two proprioceptive tests and the hamstrings to quadriceps ratio in the injured leg (threshold, $R=-0.77$, $P<0.01$; JPS $R=-0.77$, $P<0.01$).

Ochi et al. [128] tested 45 knees with ACL remnants intact to both the tibia and femur for somatosensory-evoked potentials (SEPs) and JPS. Mechanical stimulation of the ACL remnants elicited SEPs in 58 % of the knees, indicating preserved mechanoreceptors. The mean inaccuracy in JPS was greater in the injured knees compared to a control group.

Lysholm et al. [100] measured postural control in the sagittal plane in 22 chronic ACL-deficient patients and 10 uninjured subjects. Measurements were made on a force plate that was either fixed or movable according to the subject's sway and during perturbations. The ACL-deficient patients had significantly larger body sway compared to controls during single-limb stance (with eyes open and closed) on the stable surface for both the injured and contralateral limbs ($P<0.05$). The patients had significantly larger body sway on the unstable surface (with eyes open only), and a longer reaction time to perturbations in both forward and backward directions ($P<0.05$).

The effect of chronic ACL-deficiency on postural control was assessed in 20 patients and compared to a group of 55 controls by Zatterstrom and associates [170]. The patients were tested before entering a program of rehabilitation; all were symptomatic and had given up sports activities. The patients demonstrated significant differences in body sway compared to the control group, which were bilateral ($P<0.05$). The authors proposed that the impaired standing balance could have been due to physical inactivity along with a disturbed sensory feedback from the injured knee. There was no improvement in the standing balance of the ACL-deficient limbs after 3 months of rehabilitation.

The influence of anterior tibial translation, muscle peak torque, and proprioception on dynamic balance was measured in a group of 12

Table 2.1 Knee laxity, proprioception, muscle strength, and dynamic standing balance values in men with chronic ACL injuries [90]

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

NS not significant

chronic ACL-deficient subjects by Lee et al. [90]. Significant differences were found between limbs in TDPM, hamstrings strength, quadriceps strength, and postural sway (Table 2.1, $P < 0.01$). A correlation was found between TDPM and balance, with poorer proprioception resulting in poorer dynamic static balance in the ACL-deficient knee. This relationship was not found in the contralateral limb.

The effect of perturbation on standing balance was assessed in 12 chronic ACL-deficient knees by Ihara and associates [69]. 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. [63] found significant differences between patients with chronic ACL-deficiency and uninjured subjects in dynamic postural control while balancing on one limb and moving the other limb in specific directions. The patients had deficiencies in both the injured and uninjured sides.

Fig. 2.5 The single-leg hop test

Impairment in Single-Leg Hop Functional Testing

The authors [122] conducted four single-leg hop tests (single hop [Fig. 2.5], timed hop, triple hop, and triple cross-over hop) in 67 patients with chronic ACL-deficiency. When the data of only one test was considered, 49–52 % of the patients had abnormal lower limb symmetry (defined as <85 % difference between sides). When the results of two tests combined were analyzed, 62 % of the patients had abnormal symmetry. A moderate association was found between abnormal lower limb symmetry and quadriceps isokinetic peak torque ($R = 0.49$, $P < 0.01$).

Wilk and associates [162] measured lower limb symmetry during three single-leg hop tests (single hop, timed hop, triple cross-over hop) in 50 patients with chronic ACL-deficiency. These investigators reported that 47 % had abnormal limb symmetry on the single hop and 44 %, on the triple cross-over hop. A correlation was found between all three 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).

Five single-leg hop tests were evaluated by Gustavsson et al. [60] in 30 patients with ACL-deficient knees. The tests were the single hop, vertical jump, drop jump followed by a double hop for distance, square hop, and side hop. 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 to the controls ($P<0.01$). Considering data from three of the tests (vertical jump, single hop, side hop), 87 % of the subjects had an abnormal limb symmetry value in at least 1 of the tests.

Itoh et al. [73] analyzed four hop tests (figure-of-eight, up-down hop, side hop, single hop) in a group of 50 ACL-deficient knees. Abnormal symmetry was demonstrated in 68 % in the figure-of-eight test, 58 % in the up-down hop, 44 % in the side hop, and 42 % in the single hop. At least 1 abnormal test score was found in 82 % of the patients.

Katayama and associates [80] reported significant differences in the single-leg hop test between chronic ACL-deficient knees and the contralateral side ($P<0.01$). An association was found between the distance hopped and the inaccuracy of JPS ($R=-0.505$, $P<0.01$). Phillips and van Deursen [134] assessed the effectiveness of landing strategies in 30 ACL-deficient subjects compared to 30 uninjured subjects 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 compared to controls.

Critical Points

- Altered knee kinematics, quadriceps weakness, abnormal gait patterns that increase or alter joint loads and contact pressures may cause early osteoarthritis in ACL-deficient knees.
- More rapid rate of cartilage thinning in the medial tibiofemoral compartment predicted in ACL-deficient knees.
- ACL-deficient knees have significantly reduced peak external flexion moments during jogging and stair climbing, correlates with reduced quadriceps strength.
- ACL-deficient knees may experience bilateral altered proprioception and balance control.
- ≥62 % ACL-deficient knees, poor limb symmetry on single-leg hop tests.

Added Problems with Loss of Meniscus Function

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 [35, 47, 105, 107, 117, 133, 135, 138, 144, 147]. 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. In addition, the menisci provide shock absorption to the knee joint during walking and are believed to assist in overall lubrication of the articular surfaces [113, 159].

Under weight-bearing conditions, the menisci assume a significant load-bearing function in the tibiofemoral joint [4, 24, 55]. 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 [4]. The presence of intact menisci increases the contact area to 2.5 times the size compared to that of a meniscectomized joint. 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 % [140].

The menisci remain in constant congruity to the tibial and femoral articular surfaces throughout knee motion [155, 168] and are believed to contribute to knee joint stability [113, 115]. The lateral meniscus provides concavity to the lateral tibiofemoral joint due to the normal posterior convexity of the lateral tibial plateau, allowing the stabilizing effect of joint weight-bearing forces to reduce lateral compartment anterior and posterior translations [102]. Total lateral meniscectomy results in a 45–50 % decrease in total contact area and a 235–335 % increase in peak local contact pressure [129]. In a recent study, lateral meniscectomy in an ACL-deficient cadaver model resulted in significant increases in anterior translation of the lateral, central, and medial compartments during the pivot-shift test [115]. The investigators concluded that the lateral meniscus is a more important secondary restraint than the medial meniscus in resisting anterior tibial translation during combined rotatory loads during a pivoting maneuver.

Lee et al. [91] evaluated the biomechanical effects of serial meniscectomies in the posterior region of the medial meniscus. Compared with the intact state, the medial contact area decreased from 20 % (after removal of 50 % of the posterior segment) to 54 % (total meniscectomy). Medial peak contact stress increased from 43 % (50 % meniscectomy) to 136 % (total meniscectomy). The peripheral portion of the medial meniscus provides a greater contribution to increasing contact area and decreasing contact stresses compared to the central portion. Peak contact stresses increase proportionally with the amount of meniscus removed.

Medial meniscectomy performed after sectioning of the ACL results in increased anterior translation at 20° of flexion compared to knees with an intact ACL [93, 115]. The loss of the medial meniscus after an ACL injury is problematic, especially in varus-angulated knees (Figs. 2.6 and 2.7). 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 to the lateral meniscus.

Fig. 2.6 Bilateral varus malalignment

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 [82, 132, 153, 164].

Incidence of Loss of Meniscus Tissue with ACL Injuries

Research has shown that patients who sustain an ACL tear frequently damage other structures in the knee joint, with the most common being the menisci [8, 16, 23, 26, 34, 35, 49, 58, 78, 85, 104, 117, 120, 121, 147, 160]. Table 2.2 demonstrates the frequency of concomitant meniscus tears in

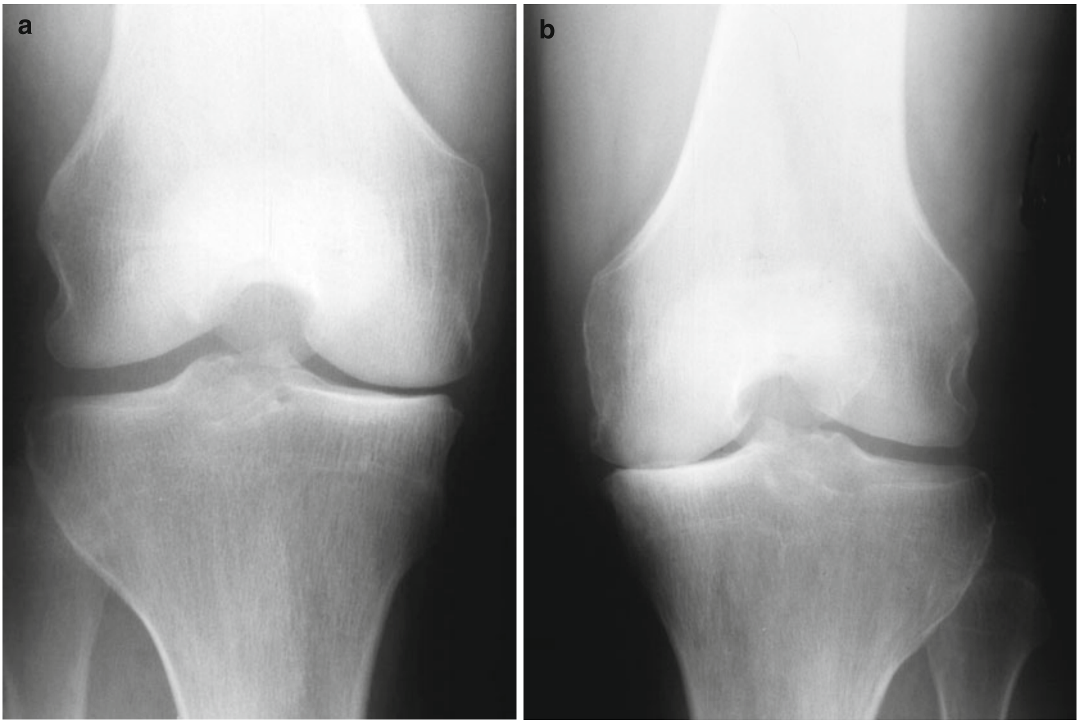


Fig. 2.7 Anteroposterior radiographs of the right (**a**) and the left (**b**) knees in a 45-year-old retired professional football player. The advanced medial tibiofemoral compartment arthritis and loss of joint space were due to bilateral varus malalignment, medial meniscectomies, and the patient's body weight of 260 lb (Reprinted with permission from Noyes and Barber-Westin [126])

patients with acute ACL ruptures, which averages 57 % (range, 24–81 %) [16, 26, 34, 35, 40, 41, 51, 70, 81, 101, 104, 117, 119, 142, 147, 154, 167]. Patients who choose nonoperative management of ACL injuries frequently sustain subsequent meniscus tears. The total incidence of meniscus pathology in patients with chronic ACL-deficient knees averages 80 %, including both meniscus tears that occur during the initial injury and those sustained subsequently.

Most studies report a higher incidence of lateral meniscus tears than medial meniscus tears in acute ACL-injured knees. However, if the injury is treated conservatively, a higher incidence of medial meniscus tears occurs with the passage of time [83, 114, 142, 146, 154]. Smith and Barrett [146] reported in a study of 575 meniscus tears in ACL-deficient knees that the medial menisci tears were frequently peripheral and involved the posterior horn. Lateral meniscus tears were commonly radial and involved the posterior horn or mid-lateral third of the meniscus. In our experience, longitudinal tears that extend into the central avascular zone in front of the popliteal tendon and hiatus are more frequently found, with radial tears being less common [124].

The overall incidence of meniscus tears increases with the passage of time in chronic ACL-deficient knees [34, 75, 114, 154]. In a series of 764 knees with ACL ruptures, Tandogan and associates [154] reported that the frequency of both medial and lateral meniscus injuries rose with increasing time from the initial injury. The odds of having a medial meniscus tear were 2.2 times higher at 2–5 years post-injury than in the first year post-injury, and 5.9 times higher >5 years post-injury. The same odds ratios for lateral meniscus tears for the same time points were 1.5 and 1.9. Cipolla et al. [34] and Keene et al. [81] both found similar trends, as acutely injured knees had a higher rate of lateral meniscus tears, but with the passage of time, a greater

Table 2.2 Occurrence of meniscus injuries in acute and chronic ACL-deficient knees

Study	No. patients	% with meniscus tear	Medial meniscus tear (%)	Lateral meniscus tear (%)	Medial and lateral meniscus tears (%)
Acute ACL injury					
DeHaven [41]	68	65	13	34	18
Noyes [121]	61	62	21	38	3
Woods [167]	99	45	18	20	7
Indelicato [70]	44	68	36	9	10
Mafulli [101]	71	24	7	15	1
Daniel [40]	190	59	25	35	11
Cipolla [34]	336	NA	31	62	NA
Neuman [117]	100	60	15	33	12
Sommerlath [147]	55	45	36	9	NA
Barrack [16]	72	72	28	19	25
Keene [81]	51	81	44	65	NA
Smith [146]	781	47	50	50	NA
All studies	1,928	57	27	32	11
Chronic ACL injury					
Woods [167]	122	88	48	17	23
Indelicato [70]	56	91	55	11	25
Fowler [51]	51	72	35	35	2
Cipolla [34]	767	NA	73	45	NA
Sommerlath [147]	80	67	36	6	25
Bray [26]	47	68	57	17	9
Conteduca [35]	460	90	67	6	17
McDaniel [104]	53	85	57	15	13
Tandogan [154]	764	73	36	16	20
Keene [81]	124	89	38	19	31
Smith [146]	284	74	58	42	NA
All studies	2,808	80	51	21	18

NA not available

number of patients suffered medial meniscus tears. Kennedy et al. [83] reported that patients had a significantly higher chance of sustaining a medial meniscus tear if 1 year had elapsed from their injury (odds ratio 7.99, $P = 0.004$). In their cohort of 300 athletic patients, a significantly higher incidence of degenerative changes were found in knees that were >6 months post-injury (odds ratio 4.04, $P = 0.005$).

Murrell et al. [114] documented meniscal and articular cartilage damage in a series of 130 patients who presented for ACL reconstruction. The effect of the chronicity of the ACL injury was determined. 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 to those who had intact menisci and whose injury occurred within 1 month of the examination. In a series of 2,616 patients aged 17–40 years, Granan et al. [59] found that the odds for sustaining a cartilage injury increased by 1 % for each month that elapsed from the injury date until ACL reconstruction. Cartilage lesions were noted to occur nearly twice as frequent if there was an associated meniscus tear.

Effects of Meniscectomy in Chronic ACL-Deficient Knees

There is substantial evidence that knees with chronic ACL-deficiency that undergo meniscectomy have an increased risk of developing early osteoarthritis (OA) compared to those that do not sustain meniscus damage [35, 47, 59, 107, 108, 117, 135, 144, 147]. Meunier et al. [107] 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 %).

Kannus and Jarvinen [77] found a trend for poorer radiographic scores, indicating advanced OA, in knees that had undergone meniscectomy compared to those that had not in a group of 40 chronic ACL-deficient knees assessed 8 ± 2 years post-injury. When the condition of the articular cartilage was documented during open arthrotomy in ACL-deficient knees by Conteduca et al. [35], a significantly greater amount of damage was found in meniscectomized knees compared to those with intact menisci. Articular cartilage damage was found in 23 % in knees with intact menisci; in 29 % of knees post-medial meniscectomy; in 30 % of knees post-lateral meniscectomy; and in 39 % of knees post-bilateral meniscectomy ($P = 0.004$).

Sherman and associates [144] followed a group of 127 patients with chronic ACL-deficiency for a mean of 6.6 years (range, 6 months–43 years); 39 had undergone meniscectomy. The three radiographic scores calculated from periarticular changes, degenerative changes, and a combination of both, found significantly poorer results after 5 years from the injury in the meniscectomized knees compared to knees with intact menisci ($P < 0.01$).

In a series of meniscectomized knees, Burks and associates [28] reported poorer radiographic and clinical results in 35 patients who had chronic ACL-deficient knees compared to 111 patients who had ACL-intact knees. The patients were evaluated 13.8–16.4 years following the total meniscectomy. Previous studies [144, 147] reported similar results, demonstrating that the negative effects of meniscectomy are amplified in ACL-deficient knees.

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 in 57 % (range, 24–81 %).
- Overall incidence meniscus tears increases with time in chronic ACL-deficient knees.
- Knees with chronic ACL-deficiency that undergo meniscectomy increased risk of early osteoarthritis compared to those with intact menisci.

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 [8, 16, 23, 116]. Noyes et al. [120, 121] examined a group of 103 chronic ACL-deficient knees (mean age, 26 years; range, 14–52) 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 to 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.

Bonamo et al. [23] followed 79 recreational athletes whose mean age was 26 years for 3–8.5 years after their ACL injury. Partial meniscectomy was performed in 67 %, and 27 % had noteworthy articular cartilage lesions detected at arthroscopy. At follow-up, 45 patients (57 %) had moderate or severe symptoms with sports and 40 % had significantly modified their activities due to these symptoms. At least 1 giving-way episode had occurred in 47 % and 73 % had a feeling of instability which affected athletic performance. An association was found between the length of follow-up and the overall results, with increasing numbers of poor results found in patients followed for ≥4 years after the original injury. The presence of a significant pivot-shift, persistent quadriceps or hamstrings strength deficits, repeat injuries, and repeat arthroscopy were indicators of a poor prognosis.

Nebelung and Wuschech [116] prospectively followed a group of 19 high-level (Olympic) athletes who were 19–30 years old for 10, 20, and 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.

Andersson and associates [8] reported on 59 patients who were followed 3.7–6 years after their injury in which all associated injuries (15 medial collateral ligament tears, 11 posterolateral tears, 19 meniscus tears) were surgically treated except the complete ACL tear. The majority of patients were competitive athletes and the mean age of the population was 25 years (range, 13–49). At follow-up, only 30 % were participating in competitive sports; 23 % at their preinjury level. The majority of patients had decreased their activity level substantially to avoid symptoms.

Barrack et al. [16] reported on 72 patients whose mean age at the time of the ACL injury was 25 years (range, 16–56). Associated meniscectomy was performed in 72 %. At follow-up, an average of 3 years (range, 8 months–7 years) later, symptoms were present in 88 % of the patients, pain in 81 %, giving-way in 64 %, swelling in 61 %, and stiffness in 50 %. Only 5 % of the patients were participating at their preinjury sports level with no problems and 21 % had not returned to any sports activity. Moderate to severe problems were found in 46 % with running, 52 % with jumping, and 58 % with turning and cutting.

Kannus and Jarvinen [78] followed 49 patients whose mean age was 32 years (range, 10–68) with complete ACL ruptures a mean of 8.0 ± 2.3 years. The evaluation revealed that 80 % had substantially decreased their activity level due to knee symptoms, with 40 % sustaining multiple giving-way reinjuries. The patients had residual strength deficits in both the quadriceps and hamstrings, with deficits averaging 20 ± 18 % and 16 ± 15 %, respectively. Only 2 patients were asymptomatic at follow-up.

Walla et al. [160] reported on 38 patients aged 18–45 years who sustained complete ACL tears. At a mean of 6 years later, 81 % had suffered significant reinjuries, the majority of which occurred within the first year. A subsequent meniscectomy had been done in 61 %.

Buss and associates [30] found a high level of problems in patients with chronic ACL-deficiency participating in low-level athletic or occupational activities. In 55 patients (mean age, 31 years; range, 18–52) following a mean of 4 years (range, 2–7.5 years), 73 % had pain mostly related to low-level athletics, and 58 % had experienced subsequent giving-way reinjuries. The authors concluded that the patients in this investigation had an approximate 50 % chance of being asymptomatic with daily activities 46 months following the injury.

Shelton et al. [143] reported the results of an aggressive return to play rehabilitation program for acute complete ACL tears in 43 competitive athletes aged 12–46 years. Following completion of rehabilitation, 13 athletes (30 %) were unable to return to athletics due to recurrent giving-way. Of the 30 that returned, 19 (63 %) experienced giving-way episodes but continued to play. Twenty-nine of the 43 patients elected ACL reconstruction due to instability; 17 of whom (57 %) were found to have meniscus tears. At the final follow-up, an average of 32 months (range, 16–51) after the original injury, only 11 patients (25 %) were participating in athletics without symptoms.

Engebretsen and Tegnander [45] followed 29 patients (mean age, 25 years) an average of 2.7 years after acute complete ACL ruptures. Only 2 patients (7 %) returned to their preinjury activity level, and 55 % reported giving-way. Hawkins et al. [61] reported on 40 patients treated initially nonoperatively for acute complete ACL tears. An average of 3.7 years later, 90 % had experienced giving-way (mostly with athletic activity), and only 10 % had resumed their preinjury level of sports activity without problems.

Kostogiannis and associates [87] followed 100 patients prospectively 1, 3, and 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 to 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 ($P<0.01$).

Critical Points

- Decline athletic participation and performance, increase 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 hamstrings strength deficits, repeat injuries, repeat arthroscopy.
- 49 patients followed mean 8.0 ± 2.3 years post-injury: 80 % had decreased activity level because of knee symptoms, and 40 % had multiple giving-way reinjuries.
- 40 patients followed 3.7 years post-injury: 10 % resumed preinjury sports without problems, and 90 % had giving-way reinjuries.

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. There exists a lack of prospective, randomized trials in regard to operative techniques (transphyseal, physeal sparing, suture repair, extra-articular tenodesis) and type of treatment (conservative versus early operative treatment) [112]. In addition, the follow-up for studies that provide outcome on ACL reconstruction is typically short, averaging just 40 months [53]. The authors agree with the more recent literature that recommends early operative correction of ACL ruptures to avoid subsequent reinjuries, meniscus injuries, and articular cartilage damage [53, 62, 76, 89, 158]. 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 [86, 109]. A recent meta-analysis of 55 studies of the outcome of ACL reconstruction in skeletally immature patients demonstrated that 44 (80 %) used either a semitendinosus-gracilis, iliotibial band, or patellar tendon autograft [53]. 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 older studies [14, 57, 103, 111] as well as more recent investigations [5, 62, 89, 109]. Lawrence et al. [89] 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 ($P=0.03$). Notably, 24 % of the patients in the delayed surgical group had irreparable medial meniscus tears, compared to just 7 % in the early reconstruction group ($P=0.01$). 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 ($P=0.04$).

Henry et al. [62] reported a greater incidence of medial meniscus tears in skeletally immature patients who attempted conservative management before ACL reconstruction. In 27 patients who were managed conservatively initially, 11 sustained meniscus tears compared to just 3 of 29 patients who underwent early ACL reconstruction ($P=0.01$). As a result, patients in the conservative group required more partial meniscectomies than those in the early reconstruction group (12 vs. 2, respectively, $P=0.01$).

Aichroth et al. [5] reported poor outcome in 23 patients who sustained complete ACL tears and were followed for 6 years postoperatively. The authors reported that knee instability was severe; episodes of pain, swelling, and giving-way were common; and the patients had given up athletics. Nearly half showed substantial radiographic (Fairbank) signs of osteoarthritis on the femoral condyle. Millett et al. [109] also reported a significant association between medial meniscus tears and time from injury to surgery ($P=0.02$). The incidence of medial meniscus tears was greater in a group of 22 patients who underwent ACL reconstruction >6 weeks from injury compared to 17 patients who had surgery <6 weeks post-injury (36 and 11 %, respectively). In addition, the number of repairable meniscus tears was decreased in the delayed surgery group, as only 4 of 18 tears were repaired compared to three of eight tears in the early reconstruction group.

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, a topic which is discussed in Chap. 17.

Critical Points

- Management of midsubstance ACL injuries in skeletally immature athletes is controversial.
- These patients may not have the maturity or emotional ability to handle the rigors of surgery and prolonged rehabilitation.
- Modern literature suggests a trend toward early operative treatment to avoid subsequent reinjuries, meniscus injuries, and articular cartilage damage
  - Conservative management has a documented high rate of subsequent meniscus tears and chondral damage.

Identification of Factors for Initial Conservative Management

A few investigators have attempted to distinguish potential "copers," or patients with ACL-deficient knees who may be able to safely return to high levels of sports activity (with minimal risk of reinjury) in the short term without undergoing reconstruction [43, 50, 67, 68, 79, 150]. Examples are athletes who sustain preseason or early season ACL ruptures who need to complete the season for an athletic scholarship, seasonal workers who wish to postpone surgery until the busy season is over, and patients in countries outside the USA who may have to wait several months or even years before undergoing an ACL reconstruction.

Strehl and Eggli [150] reported on 38 patients (mean age, 35 years; range, 16–53) with acute complete ACL ruptures who underwent a conservative treatment protocol. The authors developed a screening algorithm for consideration of conservative management which included no giving-way, low to medium sports activity levels, no additional structural damage, and a patient willing to be compliant with rehabilitation. At an average of 3.4 years (range, 1–8) later, only 14 patients (37 %) had not required ACL reconstruction due to persistent instability. Eleven patients (29 %) had not experienced giving-way during athletics, whereas 3 patients had giving-way during either sports or daily activities. Seven patients (18 %) were participating in preinjury level activities, and 1 patient had increased the activity level compared to that before the injury. Only 2 patients (5 %) were able to perform pivoting sports.

Hurd and associates [67, 68] reported the results of an algorithm and screening evaluation previously described by Fitzgerald et al. [50] for highly active patients with ACL ruptures in an effort to detect potential copers. These represented patients with isolated ACL tears that had full knee motion, no effusion, ≥70 % isometric strength compared to the opposite leg, and could hop on the injured leg without pain. Patients were enrolled in rehabilitation as required to achieve these criteria. They then underwent a screening evaluation and were classified as potential copers if they had (1) ≤1 episode of giving-way since the original injury, (2) ≥80 % limb symmetry on the 6-m timed single-leg hop test, (3) ≥80 % on the Knee Outcome Survey Activities of Daily Living [72] scale, and (4) ≥60 % on a global rating scale of 0–100. In a group of 146 potential copers, 63 (43 %) returned to IKDC level I–II sports initially. Twenty-five of these (17 %) were still participating at follow-up (time period not given) without having ACL reconstruction; 36 had elected ACL reconstruction, and 2 were lost to follow-up. The authors stated that most of the patients who underwent late ACL reconstruction did so as a planned staged approach to the management of their injury. These authors found that the preinjury activity level and the amount of increase in anterior tibial translation on knee arthrometer testing were not useful in distinguishing potential copers from non-copers.

Muscular and Neuromuscular Differences Between Copers and Non-Copers

A comparison was made in isokinetic quadriceps strength (at 60°/s) at multiple flexion angles in a study reported by Eitzen et al. [44] of 44 potential copers and 32 non-copers. The subjects also underwent a single-leg hop for distance and a single-leg 6-m timed hop. Testing was conducted 23–96 days after the injury. Significant differences were found in the absolute strength values between limbs for peak torque for all subjects ($P<0.001$), with the largest strength deficits detected at knee flexion angles <40°. Peak torque mean relative differences between limbs were 9.5 % for potential copers and 15.1 % for non-copers ($P<0.05$). At 15° and 20° of flexion, non-copers had significantly weaker strength in the ACL-deficient side compared to potential copers but had similar strength values as the noninvolved side. There was no difference in mean limb symmetry between the subgroups on both hop tests. Moderate to strong associations were found between angle-specific torque values and limb symmetry for non-copers only. The authors recommended the analysis of angle-specific isokinetic values and the 6-m timed hop test in the assessment of patients with ACL-deficiency as important tools for adequate evaluation and rehabilitation procedures.

Williams and associates [163] 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 9 as non-copers using the criteria of Fitzgerald et al. [50]. Significant atrophy of the quadriceps muscles (4.5–13 % lower muscle volume) was observed in the non-copers compared to the contralateral limb and 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" [163]. The copers' quadriceps were not atrophied, and their vastus lateralis muscles were significantly larger on their involved side (8 % greater volume) compared to the contralateral side. The study did not evaluate isokinetic muscle strength indices.

Differences in muscular activity during walking at 3 speeds between 5 copers and 5 non-copers were noted by Boerboom et al. [22]. Copers (patients who had returned to IKDC Level 1 sports activities without problems) had increased hamstring activity during stance phase. The non-copers (patients who had continued instability problems) walked with increased knee flexion compared to controls (which was symmetrical), and decreased hamstring activity.

Different gait adaptations to accommodate for ACL-deficiency have been reported between copers and non-copers. In one study [6], non-copers reduced their knee extensor moment and had smaller knee flexion angles compared to copers during stance phase of walking. The walking pattern of copers resembled a hamstring facilitation pattern, as in that observed by Boerboom et al. [22]. Rudolph and associates [137] reported similar findings, with non-copers showing reduction in knee flexion and external knee flexion moments that correlated with weak quadriceps muscle strength. More recently, Alkjaer et al. [7] revealed that non-copers walked with reduced knee compression and shear forces compared to 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 to non-copers and controls. The authors concluded the strategy adopted by the copers was more efficient to stabilize the knee joint during walking.

Courtney et al. [38] measured SEPs, JPS, and muscle activation during walking in 17 chronic ACL-deficient knees that were grouped according to coper ($n=3$), non-coper ($n=4$), and adaptor ($n=10$). Adaptors were patients who had limited their activities to avoid giving-way. Copers had proprioceptive deficits, altered SEPs, and greater and earlier hamstring activation during inclined walking. Non-copers had proprioceptive deficits and quadriceps weakness, but normal SEPs. Adaptors had an earlier gastrocnemius onset compared to copers and no proprioceptive deficit.

Courtney and Rine [39] conducted another study involving 3 copers, 4 non-copers, and 9 adaptors to assess differences in neuromuscular response to perturbation during dynamic balance testing, SEPs, and JPS. Results were similar to those previously reported for JPS and SEPs. In response to perturbation, copers had earlier and prolonged activation of hamstrings compared to the other two groups. The authors concluded that the altered postural synergies and SEPs, and not decreased proprioception (as measured by JPS), differentiated patients who were able to resume high levels of activity asymptomatically from those who were unable to do so without symptoms and limitations.

Hurd and Synder-Mackler [66] assessed the movement patterns of 21 patients early after ACL rupture during the midstance and weight acceptance phases of gait. The subjects were tested a mean of 11.4 weeks after their injury and were classified as non-copers [67] with knee instability symptoms. When compared to the uninjured limb, the subjects displayed lower sagittal plane knee excursions and peak knee angles, higher muscle co-contraction, lower knee flexion moments at peak knee extension, and higher hamstring activity and lower soleus activity. The authors concluded that non-copers stabilized their knee using a stiffening strategy that involved less knee motion and higher muscle contraction.

Critical Points

- "Copers": ACL-deficient knees who may be able to safely return to high levels of sports activity (with minimal risk of reinjury) in the short term without surgery.
- Algorithm and screening evaluation to detect copers:
  - Isolated ACL tears
  - Full knee motion, no effusion
  - ≥70 % isometric strength compared to opposite leg
  - Can hop on injured leg without pain
- Classification of copers:
  - ≤1 giving-way episode since original injury
  - ≥80 % limb symmetry on 6-m timed single-leg hop test
  - ≥80 % Knee Outcome Survey Activities of Daily Living scale
  - ≥60 % global rating scale of 0–100
- 146 potential copers: 43 % returned level I–II sports initially; 17 % still participating at follow-up.
- Non-copers
  - Weaker strength ACL-deficient side compared to potential copers
  - Significant atrophy quadriceps (4.5–13 % lower muscle volume)
  - Reduced knee flexion and external knee flexion moments on walking
  - Reduced knee compression and shear forces, overall knee joint loading, on walking.

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 [33, 141]. 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 [79]. 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.

ACL natural history studies typically report high percentages of patients who require "late" ACL reconstruction after a course of conservative treatment failed due to repeated instability episodes that occur usually during athletic activities. These percentages include 66 % reported by Shelton and associates [143], 38 % by Engebretsen and Tegnander [45], 37 % by Strehl and Eggli [150], 35 % by Barrack et al. [16], 30 % by Hawkins and associates [61], and 30 % by Daniel et al. [40]. What is more difficult to ascertain from the literature is 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 few or no symptoms with the patient's current activities, which are at their desired level.

References

1. Adachi N, Ochi M, Uchio Y et al (2002) Mechanoreceptors in the anterior cruciate ligament contribute to the joint position sense. Acta Orthop Scand 73(3):330–334
2. Ageberg E, Roberts D, Holmstrom E et al (2005) Balance in single-limb stance in patients with anterior cruciate ligament injury: relation to knee laxity, proprioception, muscle strength, and subjective function. Am J Sports Med 33(10):1527–1535
3. Ageberg E, Pettersson A, Friden T (2007) 15-year follow-up of neuromuscular function in patients with unilateral nonreconstructed anterior cruciate ligament injury initially treated with rehabilitation and activity modification: a longitudinal prospective study. Am J Sports Med 35(12):2109–2117
4. Ahmed AM, Burke DL (1983) In-vitro measurement of static pressure distribution in synovial joints – part I: tibial surface of the knee. J Biomech Eng 105(3): 216–225
5. Aichroth PM, Patel DV, Zorrilla P (2002) The natural history and treatment of rupture of the anterior cruciate ligament in children and adolescents. A prospective review. J Bone Joint Surg Br 84(1):38–41
6. Alkjaer T, Simonsen EB, Jorgensen U et al (2003) Evaluation of the walking pattern in two types of patients with anterior cruciate ligament deficiency: copers and non-copers. Eur J Appl Physiol 89(3–4): 301–308
7. Alkjaer T, Henriksen M, Simonsen EB (2011) Different knee joint loading patterns in ACL deficient copers and non-copers during walking. Knee Surg Sports Traumatol Arthrosc 19(4):615–621
8. Andersson C, Odensten M, Good L et al (1989) Surgical or non-surgical treatment of acute rupture of the anterior cruciate ligament. A randomized study with long-term follow-up. J Bone Joint Surg Am 71(7):965–974
9. Andriacchi TP (1990) Dynamics of pathological motion: applied to the anterior cruciate deficient knee. J Biomech 23(Suppl 1):99–105
10. Andriacchi TP, Birac D (1993) Functional testing in the anterior cruciate ligament-deficient knee. Clin Orthop Relat Res 288:40–47
11. Andriacchi TP, Dyrby CO, Johnson TS (2003) The use of functional analysis in evaluating knee kinematics. Clin Orthop Relat Res 410:44–53
12. Andriacchi TP, Dyrby CO (2005) Interactions between kinematics and loading during walking for the normal and ACL deficient knee. J Biomech 38(2): 293–298
13. Andriacchi TP, Scanlan SF (2009) Human movement and anterior cruciate ligament function: anterior cruciate ligament deficiency and gait mechanics. In: Noyes FR (ed) Noyes knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 130–139
14. Angel KR, Hall DJ (1989) Anterior cruciate ligament injury in children and adolescents. Arthroscopy 5(3):197–200
15. Barber-Westin SD, Heckmann TP, Noyes FR (2009) Scientific basis of rehabilitation after anterior cruciate ligament autogenous reconstruction. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 268–305
16. Barrack RL, Bruckner JD, Kniesl J et al (1990) The outcome of nonoperatively treated complete tears of the anterior cruciate ligament in active young patients. Clin Orthop Relat Res 259:192–199
17. Barrett DS (1991) Proprioception and function after anterior cruciate reconstruction. J Bone Joint Surg 73B(5):833–837
18. Bayar A, Sarikaya S, Keser S et al (2008) Regional bone density changes in anterior cruciate ligament deficient knees: a DEXA study. Knee 15(5): 373–377
19. Beard DJ, Kyberd PJ, Fergusson CM et al (1993) Proprioception after rupture of the anterior cruciate ligament. An objective indication of the need for surgery? J Bone Joint Surg 75B(2):311–315
20. Berchuck M, Andriacchi TP, Bach BR et al (1990) Gait adaptations by patients who have a deficient anterior cruciate ligament. J Bone Joint Surg Am 72(6):871–877
21. Beynnon BD, Johnson RJ, Abate JA et al (2005) Treatment of anterior cruciate ligament injuries, part 2. Am J Sports Med 33(11):1751–1767
22. Boerboom AL, Hof AL, Halbertsma JP et al (2001) Atypical hamstrings electromyographic activity as a compensatory mechanism in anterior cruciate liga-

ment deficiency. Knee Surg Sports Traumatol Arthrosc 9(4):211–216
23. Bonamo JJ, Fay C, Firestone T (1990) The conservative treatment of the anterior cruciate deficient knee. Am J Sports Med 18(6):618–623
24. Bourne RB, Finlay JB, Papadopoulos P et al (1984) The effect of medial meniscectomy on strain distribution in the proximal part of the tibia. J Bone Joint Surg Am 66(9):1431–1437
25. Branch TP, Hunter R, Donath M (1989) Dynamic EMG analysis of anterior cruciate deficient legs with and without bracing during cutting. Am J Sports Med 17(1):35–41
26. Bray RC, Dandy DJ (1989) Meniscal lesions and chronic anterior cruciate ligament deficiency. J Bone Joint Surg 71B(1):128–130
27. Brophy RH, Farooq Rai M, Zhang Z et al (2012) Molecular analysis of age and sex-related gene expression in meniscal tears with and without a concomitant anterior cruciate ligament tear. J Bone Joint Surg Am 94(5):385–393
28. Burks RT, Metcalf MH, Metcalf RW (1997) Fifteen-year follow-up of arthroscopic partial meniscectomy. Arthroscopy 13(6):673–679
29. Burstein D (2009) Tracking longitudinal changes in knee degeneration and repair. J Bone Joint Surg Am 91(Suppl 1):51–53
30. Buss DD, Min R, Skyhar M et al (1995) Nonoperative treatment of acute anterior cruciate ligament injuries in a selected group of patients. Am J Sports Med 23(2):160–165
31. Chaudhari AM, Briant PL, Bevill SL et al (2008) Knee kinematics, cartilage morphology, and osteoarthritis after ACL injury. Med Sci Sports Exerc 40(2): 215–222
32. Ciccotti MG, Kerlan RK, Perry J et al (1994) An electromyographic analysis of the knee during functional activities. II. The anterior cruciate ligament-deficient and -reconstructed profiles. Am J Sports Med 22(5):651–658
33. Ciccotti MG, Lombardo SJ, Nonweiler B et al (1994) Non-operative treatment of ruptures of the anterior cruciate ligament in middle-aged patients. Results after long-term follow-up. J Bone Joint Surg 76A(9):1315–1321
34. Cipolla M, Scala A, Gianni E et al (1995) Different patterns of meniscal tears in acute anterior cruciate ligament (ACL) ruptures and in chronic ACL-deficient knees. Classification, staging and timing of treatment. Knee Surg Sports Traumatol Arthrosc 3(3):130–134
35. Conteduca F, Ferretti A, Mariani PP et al (1991) Chondromalacia and chronic anterior instabilities of the knee. Am J Sports Med 19(2):119–123
36. Corrigan JP, Cashman WF, Brady MP (1992) Proprioception in the cruciate deficient knee. J Bone Joint Surg 74B(2):247–250
37. Costa-Paz M, Muscolo DL, Ayerza M et al (2001) Magnetic resonance imaging follow-up study of bone bruises associated with anterior cruciate ligament ruptures. Arthroscopy 17(5):445–449
38. Courtney C, Rine RM, Kroll P (2005) Central somatosensory changes and altered muscle synergies in subjects with anterior cruciate ligament deficiency. Gait Posture 22(1):69–74
39. Courtney CA, Rine RM (2006) Central somatosensory changes associated with improved dynamic balance in subjects with anterior cruciate ligament deficiency. Gait Posture 24(2):190–195
40. Daniel DM, Stone ML, Dobson BE et al (1994) Fate of the ACL-injured patient. A prospective outcome study. Am J Sports Med 22(5):632–644
41. DeHaven KE (1980) Diagnosis of acute knee injuries with hemarthrosis. Am J Sports Med 8(1):9–14
42. Demont RG, Lephart SM, Giraldo JL et al (1999) Muscle preactivity of anterior cruciate ligament-deficient and -reconstructed females during functional activities. J Athl Train 34(2):115–120
43. Eastlack ME, Axe MJ, Snyder-Mackler L (1999) Laxity, instability, and functional outcome after ACL injury: copers versus noncopers. Med Sci Sports Exerc 31(2):210–215
44. Eitzen I, Eitzen TJ, Holm I et al (2010) Anterior cruciate ligament-deficient potential copers and noncopers reveal different isokinetic quadriceps strength profiles in the early stage after injury. Am J Sports Med 38(3):586–593
45. Engebretsen L, Tegnander A (1990) Short-term results of the nonoperated isolated anterior cruciate ligament tear. J Orthop Trauma 4(4):406–410
46. Faber KJ, Dill JR, Amendola A et al (1999) Occult osteochondral lesions after anterior cruciate ligament rupture. Six-year magnetic resonance imaging follow-up study. Am J Sports Med 27(4):489–494
47. Fink C, Hoser C, Hackl W et al (2001) Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture – is sports activity a determining variable? Int J Sports Med 22(4): 304–309
48. Fischer-Rasmussen T, Jensen PE (2000) Proprioceptive sensitivity and performance in anterior cruciate ligament-deficient knee joints. Scand J Med Sci Sports 10(2):85–89
49. Fithian DC, Paxton LW, Goltz DH (2002) Fate of the anterior cruciate ligament-injured knee. Orthop Clin North Am 33(4):621–636, v
50. Fitzgerald GK, Axe MJ, Snyder-Mackler L (2000) A decision-making scheme for returning patients to high-level activity with nonoperative treatment after anterior cruciate ligament rupture. Knee Surg Sports Traumatol Arthrosc 8(2):76–82
51. Fowler PJ, Regan WD (1987) The patient with symptomatic chronic anterior cruciate ligament insufficiency. Results of minimal arthroscopic surgery and rehabilitation. Am J Sports Med 15(4):321–325
52. Friden T, Roberts D, Zatterstrom R et al (1997) Proprioception after an acute knee ligament injury: a longitudinal study on 16 consecutive patients. J Orthop Res 15(5):637–644
53. Frosch KH, Stengel D, Brodhun T et al (2010) Outcomes and risks of operative treatment of rupture

of the anterior cruciate ligament in children and adolescents. Arthroscopy 26(11):1539–1550
54. Fuentes A, Hagemeister N, Ranger P et al (2011) Gait adaptation in chronic anterior cruciate ligament-deficient patients: pivot-shift avoidance gait. Clin Biomech (Bristol, Avon) 26(2):181–187
55. Fukubayashi T, Kurosawa H (1980) The contact area and pressure distribution pattern of the knee. A study of normal and osteoarthrotic knee joints. Acta Orthop Scand 51(6):871–879
56. Gerber C, Hoppeler H, Claassen H et al (1985) The lower-extremity musculature in chronic symptomatic instability of the anterior cruciate ligament. J Bone Joint Surg Am 67(7):1034–1043
57. Graf BK, Lange RH, Fujisaki CK et al (1992) Anterior cruciate ligament tears in skeletally immature patients: meniscal pathology at presentation and after attempted conservative treatment. Arthroscopy 8(2):229–233
58. Graham GP, Fairclough JA (1988) Early osteoarthritis in young sportsmen with severe anterolateral instability of the knee. Injury 19(4):247–248
59. Granan LP, Bahr R, Lie SA et al (2009) Timing of anterior cruciate ligament reconstructive surgery and risk of cartilage lesions and meniscal tears: a cohort study based on the Norwegian National Knee Ligament Registry. Am J Sports Med 37(5):955–961
60. Gustavsson A, Neeter C, Thomee P et al (2006) A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 14(8):778–788
61. Hawkins RJ, Misamore GW, Merritt TR (1986) Followup of the acute nonoperated isolated anterior cruciate ligament tear. Am J Sports Med 14(3):205–210
62. Henry J, Chotel F, Chouteau J et al (2009) Rupture of the anterior cruciate ligament in children: early reconstruction with open physes or delayed reconstruction to skeletal maturity? Knee Surg Sports Traumatol Arthrosc 17(7):748–755
63. Herrington L, Hatcher J, Hatcher A et al (2009) A comparison of star excursion balance test reach distances between ACL deficient patients and asymptomatic controls. Knee 16(2):149–152
64. Hogervorst T, Pels Rijcken TH, van der Hart CP et al (2000) Abnormal bone scans in anterior cruciate ligament deficiency indicate structural and functional abnormalities. Knee Surg Sports Traumatol Arthrosc 8(3):137–142
65. Hopkins JT, Ingersoll CD (2000) Arthrogenic muscle inhibition: a limiting factor in joint rehabilitation. J Sport Rehabil 9:135–159
66. Hurd WJ, Snyder-Mackler L (2007) Knee instability after acute ACL rupture affects movement patterns during the mid-stance phase of gait. J Orthop Res 25(10):1369–1377
67. Hurd WJ, Axe MJ, Snyder-Mackler L (2008) A 10-year prospective trial of a patient management algorithm and screening examination for highly active individuals with anterior cruciate ligament injury: part 1, outcomes. Am J Sports Med 36(1):40–47
68. Hurd WJ, Axe MJ, Snyder-Mackler L (2008) A 10-year prospective trial of a patient management algorithm and screening examination for highly active individuals with anterior cruciate ligament injury: part 2, determinants of dynamic knee stability. Am J Sports Med 36(1):48–56
69. Ihara H, Takayama M, Fukumoto T (2008) Postural control capability of ACL-deficient knee after sudden tilting. Gait Posture 28(3):478–482
70. Indelicato PA, Bittar ES (1985) A perspective of lesions associated with ACL insufficiency of the knee. A review of 100 cases. Clin Orthop Relat Res 198:77–80
71. Ingersoll CD, Grindstaff TL, Pietrosimone BG et al (2008) Neuromuscular consequences of anterior cruciate ligament injury. Clin Sports Med 27(3):383–404, vii
72. Irrgang JJ, Snyder-Mackler L, Wainner RS et al (1998) Development of a patient-reported measure of function of the knee. J Bone Joint Surg Am 80(8):1132–1145
73. Itoh H, Kurosaka M, Yoshiya S et al (1998) Evaluation of functional deficits determined by four different hop tests in patients with anterior cruciate ligament deficiency. Knee Surg Sports Traumatol Arthrosc 6:241–245
74. Jerosch J, Prymka M (1996) Knee joint proprioception in normal volunteers and patients with anterior cruciate ligament tears, taking special account of the effect of a knee bandage. Arch Orthop Trauma Surg 115(3–4):162–166
75. Jones HP, Appleyard RC, Mahajan S et al (2003) Meniscal and chondral loss in the anterior cruciate ligament injured knee. Sports Med 33(14):1075–1089
76. Kaeding CC, Flanigan D, Donaldson C (2010) Surgical techniques and outcomes after anterior cruciate ligament reconstruction in preadolescent patients. Arthroscopy 26(11):1530–1538
77. Kannus P, Jarvinen M (1987) Long-term prognosis of nonoperatively treated acute knee distortions having primary hemarthrosis without clinical instability. Am J Sports Med 15(2):138–143
78. Kannus P, Jarvinen M (1987) Conservatively treated tears of the anterior cruciate ligament. Long-term results. J Bone Joint Surg Am 69(7):1007–1012
79. Kaplan Y (2011) Identifying individuals with an anterior cruciate ligament-deficient knee as copers and noncopers: a narrative literature review. J Orthop Sports Phys Ther 41(10):758–766
80. Katayama M, Higuchi H, Kimura M et al (2004) Proprioception and performance after anterior cruciate ligament rupture. Int Orthop 28(5):278–281
81. Keene GC, Bickerstaff D, Rae PJ et al (1993) The natural history of meniscal tears in anterior cruciate ligament insufficiency. Am J Sports Med 21(5):672–679

82. Kelly BT, Potter HG, Deng XH et al (2006) Meniscal allograft transplantation in the sheep knee: evaluation of chondroprotective effects. Am J Sports Med 34(9):1464–1477
83. Kennedy J, Jackson MP, O'Kelly P et al (2010) Timing of reconstruction of the anterior cruciate ligament in athletes and the incidence of secondary pathology within the knee. J Bone Joint Surg Br 92(3):362–366
84. Kennedy JC, Weinberg HW, Wilson AS (1974) The anatomy and function of the anterior cruciate ligament. As determined by clinical and morphological studies. J Bone Joint Surg Am 56(2): 223–235
85. Kessler MA, Behrend H, Henz S et al (2008) Function, osteoarthritis and activity after ACL-rupture: 11 years follow-up results of conservative versus reconstructive treatment. Knee Surg Sports Traumatol Arthrosc 16(5):442–448
86. Kocher MS, Saxon HS, Hovis WD et al (2002) Management and complications of anterior cruciate ligament injuries in skeletally immature patients: survey of the Herodicus Society and The ACL Study Group. J Pediatr Orthop 22(4):452–457
87. Kostogiannis I, Ageberg E, Neuman P et al (2007) Activity level and subjective knee function 15 years after anterior cruciate ligament injury: a prospective, longitudinal study of nonreconstructed patients. Am J Sports Med 35(7):1135–1143
88. Kvist J, Karlberg C, Gerdle B et al (2001) Anterior tibial translation during different isokinetic quadriceps torque in anterior cruciate ligament deficient and nonimpaired individuals. J Orthop Sports Phys Ther 31(1):4–15
89. Lawrence JT, Argawal N, Ganley TJ (2011) Degeneration of the knee joint in skeletally immature patients with a diagnosis of an anterior cruciate ligament tear: is there harm in delay of treatment? Am J Sports Med 39(12):2582–2587
90. Lee HM, Cheng CK, Liau JJ (2009) Correlation between proprioception, muscle strength, knee laxity, and dynamic standing balance in patients with chronic anterior cruciate ligament deficiency. Knee 16(5): 387–391
91. Lee SJ, Aadalen KJ, Malaviya P et al (2006) Tibiofemoral contact mechanics after serial medial meniscectomies in the human cadaveric knee. Am J Sports Med 34(8):1334–1344
92. Levy AS, Meier SW (2003) Approach to cartilage injury in the anterior cruciate ligament-deficient knee. Orthop Clin North Am 34(1):149–167
93. Levy IM, Torzilli PA, Warren RF (1982) The effect of medial meniscectomy on anterior-posterior motion of the knee. J Bone Joint Surg Am 64(6): 883–888
94. Limbird TJ, Shiavi R, Frazer M et al (1988) EMG profiles of knee joint musculature during walking: changes induced by anterior cruciate ligament deficiency. J Orthop Res 6(5):630–638
95. Logan M, Dunstan E, Robinson J et al (2004) Tibiofemoral kinematics of the anterior cruciate ligament (ACL)-deficient weightbearing, living knee employing vertical access open "interventional" multiple resonance imaging. Am J Sports Med 32(3):720–726
96. Lohmander LS, Ostenberg A, Englund M et al (2004) High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum 50(10):3145–3152
97. Lohmander LS, Englund PM, Dahl LL et al (2007) The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. Am J Sports Med 35(10):1756–1769
98. Lorentzon R, Elmqvist LG, Sjostrom M et al (1989) Thigh musculature in relation to chronic anterior cruciate ligament tear: muscle size, morphology, and mechanical output before reconstruction. Am J Sports Med 17(3):423–429
99. Louboutin H, Debarge R, Richou J et al (2009) Osteoarthritis in patients with anterior cruciate ligament rupture: a review of risk factors. Knee 16(4): 239–244
100. Lysholm M, Ledin T, Odkvist LM et al (1998) Postural control – a comparison between patients with chronic anterior cruciate ligament insufficiency and healthy individuals. Scand J Med Sci Sports 8(6):432–438
101. Maffulli N, Binfield PM, King JB et al (1993) Acute haemarthrosis of the knee in athletes. A prospective study of 106 cases. J Bone Joint Surg Br 75(6): 945–949
102. Markolf KL, Bargar WL, Shoemaker SC et al (1981) The role of joint load in knee stability. J Bone Joint Surg Am 63(4):570–585
103. McCarroll JR, Shelbourne KD, Porter DA et al (1994) Patellar tendon graft reconstruction for midsubstance anterior cruciate ligament rupture in junior high school athletes. An algorithm for management. Am J Sports Med 22(4):478–484
104. McDaniel WJ, Dameron T (1980) Untreated ruptures of the anterior cruciate ligament. A follow-up study. Journal of Bone and Joint Surgery 62A(5): 696–705
105. McDermott ID, Amis AA (2006) The consequences of meniscectomy. J Bone Joint Surg Br 88(12): 1549–1556
106. McHugh MP, Tyler TF, Nicholas SJ et al (2001) Electromyographic analysis of quadriceps fatigue after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 31(1):25–32
107. Meunier A, Odensten M, Good L (2007) Long-term results after primary repair or non-surgical treatment of anterior cruciate ligament rupture: a randomized study with a 15-year follow-up. Scand J Med Sci Sports 17(3):230–237
108. Mihelic R, Jurdana H, Jotanovic Z et al (2011) Long-term results of anterior cruciate ligament reconstruc-

tion: a comparison with non-operative treatment with a follow-up of 17–20 years. Int Orthop 35(7):1093–1097
109. Millett PJ, Willis AA, Warren RF (2002) Associated injuries in pediatric and adolescent anterior cruciate ligament tears: does a delay in treatment increase the risk of meniscal tear? Arthroscopy 18(9): 955–959
110. Mizuta H, Shiraishi M, Kubota K et al (1992) A stabilometric technique for evaluation of functional instability in anterior cruciate ligament-deficient knee. Clin J Sports Med 2:235–239
111. Mizuta H, Kubota K, Shiraishi M et al (1995) The conservative treatment of complete tears of the anterior cruciate ligament in skeletally immature patients. J Bone Joint Surg Br 77(6):890–894
112. Moksnes H, Engebretsen L, Risberg MA (2012) Management of anterior cruciate ligament injuries in skeletally immature individuals. J Orthop Sports Phys Ther 42(3):172–183
113. Mow VC, Ratcliffe A, Chern KY et al (1992) Structure and function relationships of the menisci of the knee. In: Mow VC, Arnoczky SP, Jackson DW (eds) Knee meniscus: basic and clinical foundations. Raven Press, Ltd., New York, pp 37–57
114. Murrell GA, Maddali S, Horovitz L et al (2001) The effects of time course after anterior cruciate ligament injury in correlation with meniscal and cartilage loss. Am J Sports Med 29(1):9–14
115. Musahl V, Citak M, O'Loughlin PF et al (2010) The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. Am J Sports Med 38(8):1591–1597
116. Nebelung W, Wuschech H (2005) Thirty-five years of follow-up of anterior cruciate ligament-deficient knees in high-level athletes. Arthroscopy 21(6):696–702
117. Neuman P, Englund M, Kostogiannis I et al (2008) Prevalence of tibiofemoral osteoarthritis 15 years after nonoperative treatment of anterior cruciate ligament injury: a prospective cohort study. Am J Sports Med 36(9):1717–1725
118. Neuman P, Kostogiannis I, Friden T et al (2009) Patellofemoral osteoarthritis 15 years after anterior cruciate ligament injury – a prospective cohort study. Osteoarthritis Cartilage 17(3):284–290
119. Noyes FR, Bassett RW, Grood ES et al (1980) Arthroscopy in acute traumatic hemarthrosis of the knee. Incidence of anterior cruciate tears and other injuries. J Bone Joint Surg Am 62(5):687–695, 757
120. Noyes FR, Matthews DS, Mooar PA et al (1983) The symptomatic anterior cruciate-deficient knee. Part II: the results of rehabilitation, activity modification, and counseling on functional disability. J Bone Joint Surg Am 65(2):163–174
121. Noyes FR, Mooar PA, Matthews DS et al (1983) The symptomatic anterior cruciate-deficient knee. Part I: the long-term functional disability in athletically active individuals. J Bone Joint Surg Am 65(2): 154–162
122. Noyes FR, Barber SD, Mangine RE (1991) Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med 19(5):513–518
123. Noyes FR, Schipplein OD, Andriacchi TP et al (1992) The anterior cruciate ligament-deficient knee with varus alignment. An analysis of gait adaptations and dynamic joint loadings. Am J Sports Med 20(6):707–716
124. 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
125. Noyes FR, Barber-Westin SD (2009) Meniscus transplantation: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 772–805
126. Noyes FR, Barber-Westin SD (2009) Primary, double, and triple varus knee syndromes: diagnosis, osteotomy techniques, and clinical outcomes. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 821–895
127. Nyland J, Fisher B, Brand E et al (2010) Osseous deficits after anterior cruciate ligament injury and reconstruction: a systematic literature review with suggestions to improve osseous homeostasis. Arthroscopy 26(9):1248–1257
128. Ochi M, Iwasa J, Uchio Y et al (2002) Induction of somatosensory evoked potentials by mechanical stimulation in reconstructed anterior cruciate ligaments. J Bone Joint Surg Br 84(5):761–766
129. Paletta GA, Manning T, Snell E et al (1997) The effect of allograft meniscal replacement on intraarticular contact area and pressures in the human knee. A biomechanical study. Am J Sports Med 25(5): 692–698
130. Palmieri-Smith RM, Thomas AC (2009) A neuromuscular mechanism of posttraumatic osteoarthritis associated with ACL injury. Exerc Sport Sci Rev 37(3):147–153
131. Patel RR, Hurwitz DE, Bush-Joseph CA et al (2003) Comparison of clinical and dynamic knee function in patients with anterior cruciate ligament deficiency. Am J Sports Med 31(1):68–74
132. Pena E, Calvo B, Martinez MA et al (2005) Finite element analysis of the effect of meniscal tears and meniscectomies on human knee biomechanics. Clin Biomech (Bristol, Avon) 20(5): 498–507
133. Petty CA, Lubowitz JH (2011) Does arthroscopic partial meniscectomy result in knee osteoarthritis? A systematic review with a minimum of 8 years' follow-up. Arthroscopy 27(3):419–424
134. Phillips N, van Deursen RW (2008) Landing stability in anterior cruciate ligament deficient versus healthy individuals: a motor control approach. Phys Ther Sport 9(4):193–201

135. Roos EM (2005) Joint injury causes knee osteoarthritis in young adults. Curr Opin Rheumatol 17(2): 195–200
136. Roos H, Adalberth T, Dahlberg L et al (1995) Osteoarthritis of the knee after injury to the anterior cruciate ligament or meniscus: the influence of time and age. Osteoarthritis Cartilage 3(4):261–267
137. Rudolph KS, Axe MJ, Buchanan TS et al (2001) Dynamic stability in the anterior cruciate ligament deficient knee. Knee Surg Sports Traumatol Arthrosc 9(2):62–71
138. Salata MJ, Gibbs AE, Sekiya JK (2010) A systematic review of clinical outcomes in patients undergoing meniscectomy. Am J Sports Med 38(9): 1907–1916
139. Schutte MJ, Dabezies EJ, Zimny ML et al (1987) Neural anatomy of the human anterior cruciate ligament. J Bone Joint Surg 69A(2):243–247
140. Seedhom BB, Hargreaves DJ (1979) Transmission of the load in the knee joint with special reference to the role of the menisci. Part II. Experimental results, discussion, and conclusions. Eng Med 8:220–228
141. Segawa H, Omori G, Koga Y (2001) Long-term results of non-operative treatment of anterior cruciate ligament injury. Knee 8(1):5–11
142. Shelbourne KD, Nitz PA (1991) The O'Donoghue triad revisited. Combined knee injuries involving anterior cruciate and medial collateral ligament tears. Am J Sports Med 19(5):474–477
143. Shelton WR, Barrett GR, Dukes A (1997) Early season anterior cruciate ligament tears. A treatment dilemma. Am J Sports Med 25(5):656–658
144. Sherman MF, Warren RF, Marshall JL et al (1988) A clinical and radiographical analysis of 127 anterior cruciate insufficient knees. Clin Orthop Relat Res 227:229–237
145. Shiavi R, Zhang LQ, Limbird T et al (1992) Pattern analysis of electromyographic linear envelopes exhibited by subjects with uninjured and injured knees during free and fast speed walking. J Orthop Res 10(2):226–236
146. Smith JP 3rd, Barrett GR (2001) Medial and lateral meniscal tear patterns in anterior cruciate ligament-deficient knees. A prospective analysis of 575 tears. Am J Sports Med 29(4):415–419
147. Sommerlath K, Gillquist J (1992) The long-term course of various meniscal treatments in anterior cruciate ligament deficient knees. Clin Orthop Relat Res 283:207–214
148. St Clair Gibson A, Lambert MI, Durandt JJ et al (2000) Quadriceps and hamstrings peak torque ratio changes in persons with chronic anterior cruciate ligament deficiency. J Orthop Sports Phys Ther 30(7):418–427
149. Stein LN, Fischer DA, Fritts HM et al (1995) Occult osseous lesions associated with anterior cruciate ligament tears. Clin Orthop Relat Res 313: 187–193
150. Strehl A, Eggli S (2007) The value of conservative treatment in ruptures of the anterior cruciate ligament (ACL). J Trauma 62(5):1159–1162
151. Suter E, Herzog W (2000) Does muscle inhibition after knee injury increase the risk of osteoarthritis? Exerc Sport Sci Rev 28(1):15–18
152. Swanik CB, Lephart SM, Swanik KA et al (2004) Neuromuscular dynamic restraint in women with anterior cruciate ligament injuries. Clin Orthop Relat Res 425:189–199
153. Szomor ZL, Martin TE, Bonar F et al (2000) The protective effects of meniscal transplantation on cartilage. An experimental study in sheep. J Bone Joint Surg Am 82(1):80–88
154. Tandogan RN, Taser O, Kayaalp A et al (2004) Analysis of meniscal and chondral lesions accompanying anterior cruciate ligament tears: relationship with age, time from injury, and level of sport. Knee Surg Sports Traumatol Arthrosc 12(4): 262–270
155. Thompson WO, Thaete FL, Fu FH et al (1991) Tibial meniscal dynamics using three-dimensional reconstruction of magnetic resonance images. Am J Sports Med 19:210–216
156. Tsepis E, Vagenas G, Giakas G et al (2004) Hamstring weakness as an indicator of poor knee function in ACL-deficient patients. Knee Surg Sports Traumatol Arthrosc 12(1):22–29
157. Tsepis E, Vagenas G, Ristanis S et al (2006) Thigh muscle weakness in ACL-deficient knees persists without structured rehabilitation. Clin Orthop Relat Res 450:211–218
158. Utukuri MM, Somayaji HS, Khanduja V et al (2006) Update on paediatric ACL injuries. Knee 13(5): 345–352
159. Voloshin AS, Wosk J (1983) Shock absorption of meniscectomized and painful knees: a comparative in vivo study. J Biomed Eng 5(2):157–161
160. Walla DJ, Albright JP, McAuley E et al (1985) Hamstring control and the unstable anterior cruciate ligament-deficient knee. Am J Sports Med 13(1): 34–39
161. Wexler G, Hurwitz DE, Bush-Joseph CA et al (1998) Functional gait adaptations in patients with anterior cruciate ligament deficiency over time. Clin Orthop Relat Res 348:166–175
162. Wilk KE, Romaniello WT, Soscia SM et al (1994) The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. J Orthop Sports Phys Ther 20(2):60–73
163. Williams GN, Snyder-Mackler L, Barrance PJ et al (2005) Quadriceps femoris muscle morphology and function after ACL injury: a differential response in copers versus non-copers. J Biomech 38(4): 685–693
164. Wilson W, van Rietbergen B, van Donkelaar CC et al (2003) Pathways of load-induced cartilage damage causing cartilage degeneration in the knee after meniscectomy. J Biomech 36(6):845–851
165. Wojtys EM, Huston LJ (1994) Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities. Am J Sports Med 22(1): 89–104

166. Wojtys EM, Huston LJ (2000) Longitudinal effects of anterior cruciate ligament injury and patellar tendon autograft reconstruction on neuromuscular performance. Am J Sports Med 28(3): 336–344
167. Woods GW, Chapman DR (1984) Repairable posterior menisco-capsular disruption in anterior cruciate ligament injuries. Am J Sports Med 12(5): 381–385
168. Yao J, Lancianese SL, Hovinga KR et al (2008) Magnetic resonance image analysis of meniscal translation and tibio-menisco-femoral contact in deep knee flexion. J Orthop Res 26(5):673–684
169. Yoon KH, Yoo JH, Kim KI (2011) Bone contusion and associated meniscal and medial collateral ligament injury in patients with anterior cruciate ligament rupture. J Bone Joint Surg Am 93A(16): 1510–1518
170. Zatterstrom R, Friden T, Lindstrand A et al (1994) The effect of physiotherapy on standing balance in chronic anterior cruciate ligament insufficiency. Am J Sports Med 22(4):531–536

ACL Reconstruction: Chondroprotective Effects, Risks of Reinjury

3

Frank R. Noyes and Sue D. Barber-Westin

Contents

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 potentially prevent or delay the onset of 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. Some authors have stated that the ACL injury itself may lead to OA regardless of the treatment selected and subsequent joint loading over ensuing years [9, 51]. 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, alteration in the biochemical environment, and chondral fractures or lesions [10, 24, 45, 46, 89]. Other factors that may play a role include excessive uncorrected varus or valgus lower limb malalignment, obesity, familial predisposition, and long-term participation in high impact sports activities [25, 35, 45, 51, 93].

The problem exists that ACL reconstruction does not fully restore normal knee kinematics, despite advanced surgical procedures and rehabilitation. The native ACL is a complex structure composed of individual fibers and fiber regions which are loaded throughout knee motion to resist anterior tibial translation and the combined motions of anterior tibial translation and internal tibial rotation [66, 68]. Recently, studies have documented the problem of vertical ACL graft orientation that resulted from poor tunnel

F.R. Noyes, M.D.
Cincinnati Sportsmedicine and Orthopaedic Center, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

S.D. Barber-Westin, B.S. (✉)
Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA
e-mail: sbwestin@csmref.org

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_3, © Springer-Verlag Berlin Heidelberg 2012

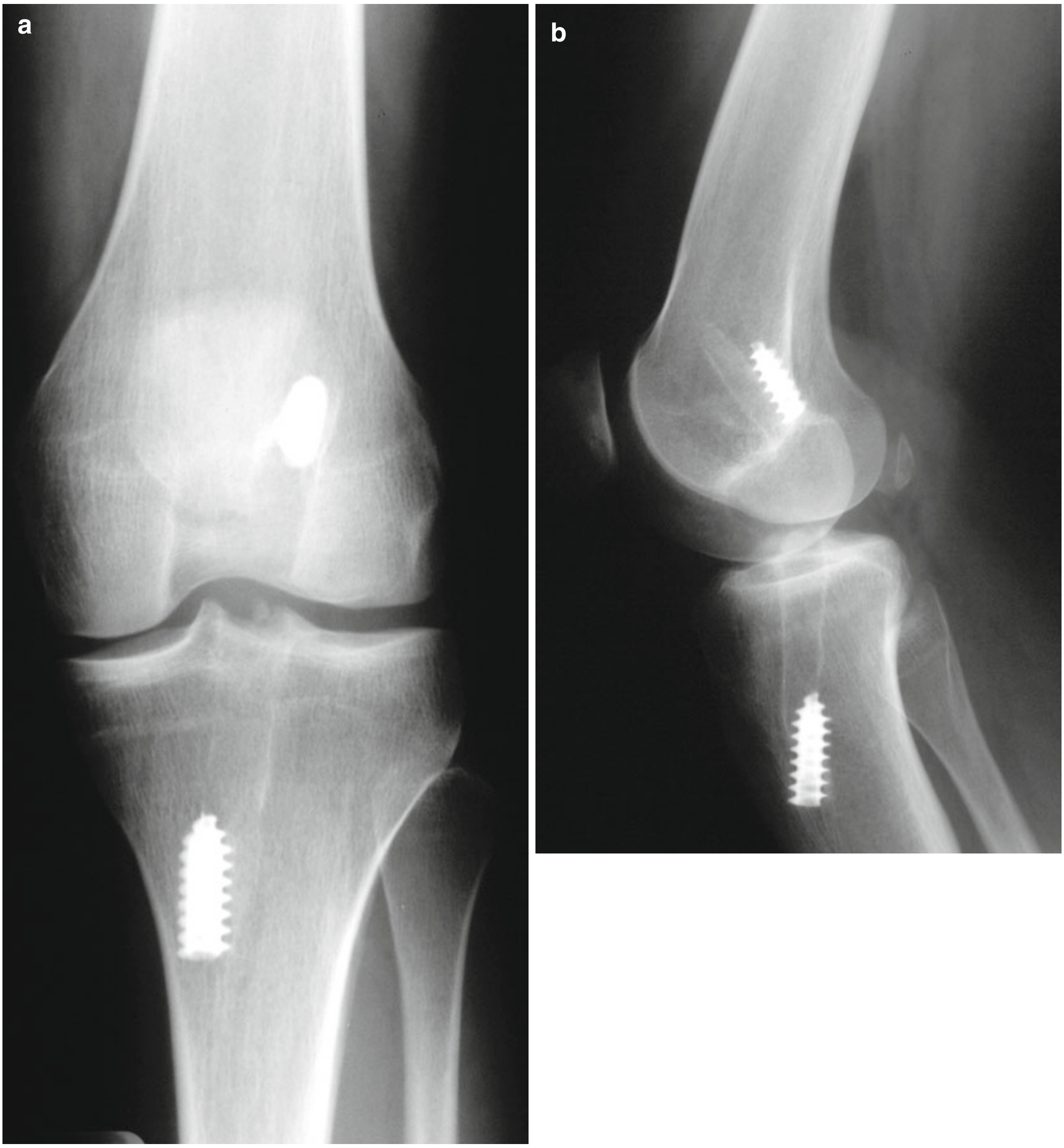


Fig. 3.1 Anteroposterior (**a**) and lateral (**b**) radiographs of the left knee after a failed ACL reconstruction. Note the vertical graft orientation of the tunnels and excessive anterior placement of the femoral tunnel (From Noyes and Barber-Westin [63]; with permission from SAGE Publications, Inc.)

placement through the use of endoscopic surgical techniques (Fig. 3.1) [5, 66]. In some patients, this graft orientation results in a return of the pivot shift, knee instability, and subsequent revision ACL reconstruction [48]. Authors have postulated that the abnormal knee kinematics documented after ACL reconstruction may be one of the factors causing eventual OA [9, 45].

Another 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 and conservative management of this injury using modern operative procedures and rehabilitation programs. Secondly, while studies historically have used plain radiographs to rate OA, more advanced technology

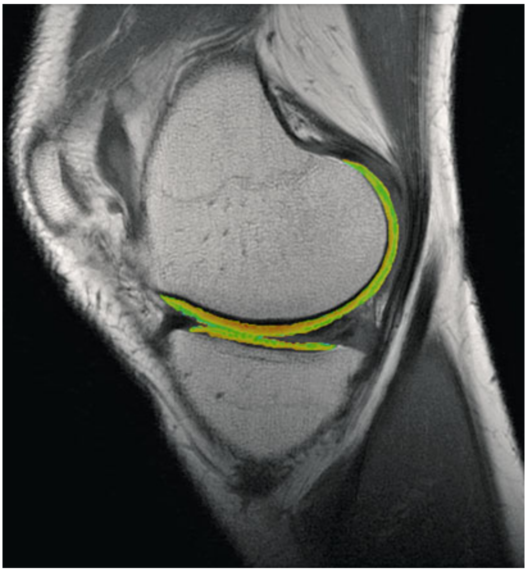


Fig. 3.2 T2 mapping shows intact articular cartilage with no focal prolongation of relaxation times

is now available such as magnetic resonance imaging (MRI) with T2 mapping which determines with higher accuracy the status of the articular cartilage (Fig. 3.2). There exists tremendous variability within studies of the populations followed in terms of chronicity of the ACL injury, documentation of reinjuries that occurred, preexisting articular cartilage damage, loss of meniscus tissue, and sports activity levels. In order to understand the chondroprotective effects of ACL reconstruction, these factors should be accounted for and populations sorted accordingly.

Critical Points

- Outcome of 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, familial predisposition, 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.

Long-Term Studies on ACL Reconstruction and Osteoarthritis

The factor of meniscectomy correlates with radiographic evidence of OA in nearly all long-term studies in which cohorts are sorted according to intact versus meniscectomized knees [3, 13, 30, 31, 33, 38, 45, 49, 53, 81, 82, 95]. It is imperative to conduct this analysis because otherwise data from entire cohorts reported collectively may be misleading, as discussed below. It is also important to note that the majority of OA findings reported in the literature are mild or moderate (Table 3.1); few severe degenerative changes have been reported and there appears to be no correlation with mild or moderate radiographic OA and clinical symptoms. However, the longest clinical studies published to date have followed patients for 17–20 years after ACL reconstruction [3, 19, 49]. As investigations obtain longer follow-up periods, one may speculate that the OA findings (especially in meniscectomized knees) will become more severe and correlate with clinical symptoms such as loss of extension and swelling with daily activities.

Ait Si Selmi [3] and associates followed 103 patients 11–17 years after a combined ACL bone-patellar tendon-bone (B-PT-B) autograft and iliotibial band extra-articular procedure. The majority of patients had the operation for chronic ACL ruptures, with an average interval between the injury and surgery of 36.6 months. The International Knee Documentation Committee (IKDC) ratings for the ACL were normal or nearly normal in 59 %, abnormal in 36 %, and severely abnormal in 4 %. IKDC x-ray ratings taken from 45° posteroanterior (PA) weight-bearing views in knees with intact menisci were

Table 3.1 Prevalence of radiographic osteoarthritis in long-term ACL reconstruction studies

Study	No.	ACL graft	OA grade 0	OA grade 1	OA grade 2	OA grade 3	
	Follow-up years		IKDC normal	IKDC nearly normal	IKDC abnormal	IKDC severely abnormal	Correlation OA and meniscectomy
Li et al. [45]	249 2–20 year	BPTB or STG autograft Allograft	32 %	42 %	17 %	9 %	Medial meniscectomy (P=.001)
Hanypsiak et al. [30]	44 12 year	BPTB or STG autograft	30 %	32 %	48 %	0 %	Meniscectomy (P=NA)
Kessler et al. [42]	60 7–16 year	BPTB allograft	45 %	10 %	42 %	3 %	NA
Pinczewski et al. [74]	128 10 year	BPTB autograft (N=59) STG autograft (N=69)	61 % 81 %	36 % 17 %	3 % 1 %	0 % 0 %	NA
Ait Si Selmi et al. [3]	103 11–17 year	BPTB autograft + ili-otibial band extra-articular	51 %	22 %	23 %	5 %	Medial meniscectomy (P=.002)
Drogset et al. [19]	32 17 year	BPTB autograft	88 %	6 %	3 %	0 %	NA
Salmon et al. [81]	49 13 year	BPTB autograft	37 %	42 %	19 %	2 %	Medial meniscectomy (P=.006)
Hart et al. [31]	31 10 year	BPTB autograft	29 %	42 %	26 %	3 %	Meniscectomy (P<.05)
Hertel et al. [33]	95 9–12 year	BPTB autograft	63 %	13 %	24 %	0 %	Meniscectomy (P=NA)
Fink et al. [25]	46 10–13 year	BPTB autograft	22 %	28 %	37 %	13 %	NA
O'Neil [73]	225 6–11 year	BPTB autograft (N=136) STG autograft (N=63)	88 %	9 %	2 %	1 %	None
Shelbourne and Gray [82]	482 5–15 year	BPTB autograft	78 %	11 %	10 %	1 %	Medial and bilateral meniscectomy (P=NA)
Jomha et al. [38]	59 7 year	BPTB autograft	43 %	41 %	13 %	2 %	Medial and lateral meniscectomy (P<.05)

OA grade = Kellgren-Lawrence, Ahlback, or International Knee Documentation Committee (IKDC) rating systems
BPTB bone-patellar tendon-bone, *STG* semitendinosus-gracilis, *NA* not available

normal or nearly normal in 89 % and abnormal in 11 %. In knees that had medial meniscectomies, 63 % were normal or nearly normal and 37 % were abnormal (Table 3.2). In knees that had lateral meniscectomies, 86 % were normal or nearly normal, 5 % were abnormal, and 9 % were severely abnormal. Two factors correlated with radiographic OA: medial meniscectomy (P=.002) and increased anterior tibial translation (P=.001). The mean age of the patients at follow-up was

Table 3.2 Prevalence of radiographic osteoarthritis in long-term ACL reconstruction studies: effect of meniscectomy

Study	No.	ACL graft	OA grade 0		OA grade 1		OA grade 2		OA grade 3	
			IKDC normal		IKDC nearly normal		IKDC abnormal		IKDC severely abnormal	
	Follow-up year		Menisc	Intact	Menisc	Intact	Menisc	Intact	Menisc	Intact
Ait Si Selmi et al. [3]	103 11–17 year	BPTB autograft + iliotibial band extra-articular	63 % (M) 86 % (L)	89 %[a]	–	–	37 % (M) 5 % (L)	11 %	0 % (M) 9 % (L)	0 %
Hart et al. [31]	31 10 year	BPTB autograft	19 %	40 %	37 %	47 %	37 %	13 %	6 %	0 %
Hertel et al. [33]	95 9–12 year	BPTB autograft	76 %[a]	97 %[a]	–	–	24 %	3 %	0 %	0 %
Shelbourne and Gray [82]	482 5–15 year	BPTB autograft	66 % (M) 80 % (L) 58 % (B)	88 %	11 % (M) 11 % (L) 17 % (B)	9 %	20 % (M) 9 % (L) 22 % (B)	3 %	3 % (M) 0 % (L) 3 % (B)	0 %

OA grade = Kellgren-Lawrence, Ahlback, or International Knee Documentation Committee (IKDC) rating systems
Menisc meniscectomy, *BPTB* bone-patellar tendon-bone, *(M)* medial meniscus, *(L)* lateral meniscus, *(B)* bilateral meniscectomy
[a]Grades 0 and 1 combined into 1 category

42 years (range, 29–61); 9 % were >50 years old. Radiographic OA was present in only 9 % of the contralateral knees. The authors concluded that the long-term results of the operation were acceptable in knees with an intact medial meniscus.

Drogset et al. [19] found a "surprisingly low prevalence of OA" 17 years following ACL B-PT-B autograft reconstruction. The 32 patients in this cohort underwent reconstruction for acute ACL ruptures. All but 1 patient rated their knee function as excellent or good. Knee arthrometer testing showed that 70 % of the patients had <3 mm increased anterior tibial translation, 27 % had 3–5 mm, and 3 % had >5 mm. Radiographic OA on 45° weight-bearing views was detected in four knees (11 %); however, the authors did not provide information regarding meniscus function.

Salmon et al. [81] conducted a longitudinal analysis of 49 patients for 13 years after ACL B-PT-B autograft reconstruction performed for both acute and chronic ACL ruptures. At the final follow-up, 96 % had no giving-way with moderate or strenuous activities and 92 % had no pain with these activities. Nearly one-half of the population was participating in IKDC level 1 or 2 athletic activities. Overall, the prevalence of radiographic OA on 30° weight-bearing PA views increased with the passage of time from 5 years postoperative (25 %), to 7 years postoperative (41 %), to 13 years postoperative (79 %, $P=.01$). At final follow-up, radiographic OA was noted in 87 % of medial meniscectomized knees compared to 50 % with intact menisci ($P=.006$). Increased anterior tibial translation ($P=.04$) and loss of knee extension ($P=.05$) also correlated with radiographic OA. ACL graft ruptures occurred in nine patients (18 %). The authors noted that patients who had undergone meniscectomy at the time of ACL reconstruction had increasing laxity with time and greater odds of graft rupture by a factor of 6.

Kessler and associates [42] followed 60 patients for 7–16 years after ACL B-PT-B allograft reconstruction. All patients had intact menisci at the time of the operation; seven required subsequent meniscectomy. The overall IKDC knee exam grades were normal or nearly normal in 71 %, abnormal in 20 %, and severely abnormal in 8 %. The mean anterior tibial translation on KT-1000 testing was 3.9 mm (range, 0–12 mm); however, the rate of graft failure was not provided. Radiographic OA, defined as grades II and III on the Kellgren-Lawrence rating scale, was noted in 45 %. The authors did not determine if subsequent meniscectomy increased the risk of OA. A significantly lower rate of meniscus surgery performed after the reconstruction was noted in comparison with a group of 68 patients with ACL ruptures treated nonoperatively (10 % vs. 26 %, $P<.03$).

Li and coauthors [45] reported that obesity (body mass index >30), concurrent medial meniscectomy, Outerbridge ≥grade 2 ratings of the medial femoral condyle, and increased length of follow-up were strongly related to the development of radiographic OA. Their study included 249 patients who were followed a mean of 7.86 years after endoscopic ACL reconstruction, which the authors stated was a nonanatomic procedure. In the reconstructed knees, 17, 17, and 11 % of patients had ≥grade 2 Kellgren-Lawrence grades in the medial, lateral, and patellofemoral compartments, respectively. In the contralateral knee, 3, 1, and 3 % of patients had these findings.

Nakata et al. [53] observed 61 patients who underwent ACL allograft free tendon reconstruction for 10 years postoperatively. At follow-up, all but 1 patient rated the overall knee condition as normal or nearly normal. A positive pivot-shift test was detected in 7 %. Radiographic OA assessed with 30° PA weight-bearing views was detected in 41 % of the patients overall. OA changes were found in 13 of 15 (87 %) meniscectomized knees compared to 12 of 46 (26 %) knees with intact menisci ($P<.05$).

Pinczewski and associates [74] performed a longitudinal comparison of the results of 74 patients who underwent ACL semitendinosus-gracilis (STG) autograft reconstruction and 75 patients who underwent B-PT-B autograft reconstruction. In 75 %, the reconstruction was done less than 12 weeks after the injury, and in all patients, the menisci were intact. At the final follow-up, 97 % of the patients who had not experienced a reinjury rated their knee condition as normal or nearly normal. There was no difference in graft rupture rates (8 % in B-PT-B group and 13 % in STG group) or in the contralateral ACL injury rates (22 % in B-PT-B group and 10 % in the STG group). The prevalence of radiographic OA increased with the passage of time. In the B-PT-B group, OA was detected in 4 % at 2 years, 26 % at 5 years, 34 % at 7 years, and 39 % at 10 years postoperatively. In the STG group, OA was detected in 1 % at 2 years, 8 % at 5 years, 9 % at 7 years, and 18 % at 10 years postoperatively. The authors did not assess the effect of subsequent meniscectomy on OA, which had been performed in 13 patients.

Hart and associates [31] evaluated 31 patients who underwent ACL B-PT-B autograft reconstruction 9–13 years postoperatively. Sixteen patients had concurrent meniscectomy. Weight-bearing radiographs and single-photon emission computed tomography (SPECT) were performed to assess for OA and compared to the contralateral normal knees. The authors reported that OA was detected on radiographs in 44 % of meniscectomized knees compared to 13 % of knees with intact menisci ($P<.05$). The SPECT scans demonstrated OA in 31 % of meniscectomized knees and in 7 % of knees with intact menisci ($P<.05$).

Hertel et al. [33] followed 95 patients who underwent ACL B-PT-B autograft reconstruction for acute and chronic injuries for 9–12 years postoperatively. Concurrent meniscectomy had been done in 43 patients. No patient had >5 mm increase in anterior tibial translation on KT-1000 testing. A positive pivot shift was detected in 3 %. Normal or nearly normal knee function was reported in 95 %. Weight-bearing radiographs showed 24 % had radiographic OA rated as IKDC abnormal. Of the patients who underwent meniscectomy, normal or nearly normal IKDC ratings were found in 76 % and abnormal ratings, in 24 %. Of the patients with intact menisci, 97 % had normal or nearly normal IKDC ratings and 3 %, abnormal ratings.

Wu and associates [95] reported the results of 63 patients followed for 10 years after ACL B-PT-B autograft reconstruction for acute and chronic ruptures. Meniscectomized knees had greater symptoms of pain, swelling, and giving-way ($P<.05$) compared to knees with intact menisci. All patients who underwent complete meniscectomy had radiographic OA, compared to 2 patients (8 %) with intact menisci. The study also demonstrated that an increasing amount of meniscal resection was a predictor of poorer functional outcome.

Fink et al. [25] followed 46 patients who underwent ACL B-PT-B autograft reconstruction 10–13 years postoperatively. One-half of the cohort underwent a concurrent meniscectomy. The authors reported that 22 % had no radiographic OA changes. Fairbank's grade 1 was noted in 28 %, grade 2 in 37 %, and grade 3 in 13 %. There was no correlation between the degree of OA and patient sports activity levels. There was no difference in the degree of radiographic OA when the results were compared to a group of 25 patients treated conservatively for the ACL rupture in whom 48 % underwent meniscectomy.

Shelbourne and Gray [82] followed 482 patients 5–15 years after ACL B-PT-B autograft reconstruction. Either before or during the reconstruction, the lateral meniscus was removed in 74, the medial meniscus was removed in 113, and both menisci were removed in 60. IKDC radiographic grades of normal or nearly normal were found in 97 % of patients with intact menisci compared to 91 % of lateral meniscectomized knees, 77 % of medial meniscectomized knees, and 75 % of bilateral meniscectomized knees. Patients with medial or bilateral meniscectomized knees had significantly greater anterior tibial translation on KT-1000 testing ($P=.006$). Meniscectomy correlated with lower subjective scores compared to a control group and to patients with intact menisci and normal articular cartilage surfaces ($P=.002$). Only 4 patients (1.6 %) with intact menisci at the time of the ACL reconstruction suffered subsequent meniscus tears. The authors concluded that ACL reconstruction has a protective effect for at least 10 years when performed in knees with normal menisci and articular cartilage surfaces.

Jomha et al. [38] followed 59 patients for 7 years after ACL B-PT-B autograft reconstruction for acute and chronic ruptures. The evaluation revealed that 56 patients (95 %) rated their knee function as normal or nearly normal. Three patients had a grade 3 Lachman test and 1 had a fully positive pivot shift. Only 31 % had intact menisci. Both medial ($P<.001$) and lateral ($P<.05$) meniscectomy correlated with radiographic OA. For all patients, OA degenerative changes were more advanced when the reconstruction was done >12 weeks after the injury ($P<.05$). IKDC radiographic grades were normal in 43 %, nearly normal in 41 %, abnormal in 13 %, and severely abnormal in 2 %. Meniscectomy also correlated with low overall IKDC grades, with those patients having a 34 % chance of an abnormal or severely abnormal score compared with 15 % of patients with intact menisci.

O'Neill [73] followed 225 patients who received either a B-PT-B or STG autograft for 6–11 years postoperatively. There were no differences between groups in radiographic OA; only 2 % had abnormal and 1 % had severely abnormal IKDC ratings. There was no relationship found in this study between meniscectomy or type of graft and radiographic ratings.

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.
- 11–17-year follow-up 103 patients: IKDC radiographic grade normal or nearly normal in 89 % knees intact menisci, 63 % knees medial meniscectomy, 86 % knees lateral meniscectomy.
- 13-year follow-up 49 patients: radiographic OA 87 % knees medial meniscectomy, 50 % knees intact menisci.
- 10-year follow-up 61 patients: radiographic OA 87 % meniscectomized knees, 26 % knees intact menisci.
- 10-year follow-up 63 patients: radiographic OA 100 % meniscectomized knees, 8 % knees intact menisci.

Osteochondral Lesions with ACL Injury: Precursor to Future Osteoarthritis?

Occult injuries to the bone, commonly referred to as bone bruises, occur with ACL ruptures in at least 80 % of knees in the acute time period (Fig. 3.3) [1, 22, 54, 76, 78, 84, 85, 96, 97]. The injury causes an anterior subluxation of the tibia relative to the femur that results in the lateral femoral condyle impacting against the lateral 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, although medial side bone contusions have been reported [97]. Bone bruises are believed to be the result of microfracture of the medullary trabeculae and hemorrhage that occurs at the time of the injury [52]. Authors report that in many knees, plain radiographs and arthroscopy show no abnormalities and that the bone bruise is only evident on MRI [21, 23, 92]. Other osseous injuries may occur during ACL ruptures, including subchondral fractures, osteochondral fractures, and stress fractures [43, 55, 97].

The natural history of bone bruises remains unclear, especially those associated with ACL injuries. Two recently published studies that longitudinally followed patients with acute ACL ruptures for several years after the injury demonstrated a strong potential for continued joint deterioration, regardless of the initial bone bruise location. A prospective study was conducted of 40 patients who underwent baseline MRI within 8 weeks of the injury and then 7–11 years later [76]. 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 odds ratio effect of cartilage loss over the medial tibial plateau compared with the surgical group.

Frobell [27] 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). The authors reported that 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 [75] 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 effect other cartilage surfaces of the knee joint.

A high association between bone bruises and articular cartilage damage observed at arthroscopy was reported by Nishimori et al. [54]. In a study of 39 patients who underwent ACL hamstring tendon reconstruction, 35 (90 %) had bone bruises in the lateral compartment. Of these, 33 (94 %) had articular cartilage lesions on the lateral femoral condyle and 28 (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 following a successful ACL reconstruction.

Some investigators [14, 23, 86, 89, 92] provide evidence that bone bruises do not all resolve and some remain visible on MRI for many months after the injury. Nakamae et al. [52] summarized the published clinical studies and noted that large bone bruises associated with subchondral or osteochondral injuries, or geographic bruises on MRI, appear to persist for years after the injury. The signal alterations may reflect early stages of posttraumatic OA. Davies et al. [15] noted that the speed of resolution of bone bruises is related to the presence of an associated osteochondral injury. These authors suggested, due to persistent problems 3 months after acute knee injuries in patients with bone bruises, the need for longer and more careful rehabilitation before surgery.

Costa-Paz and associates [14] reported that type III bone bruises (disruption or depression of the normal contour of the cortical surface, $N=5$) did not resolve and were still evident with cartilage thinning or cortical depression on follow-up MRI 24–64 months after the injury. Type I ($N=13$) and II ($N=11$) lesions did resolve in that investigation. Faber et al. [23] followed 23 patients who underwent STG autograft reconstruction for acute ACL injuries and reported persistent marrow changes on MRI in 65 % of the patients 6 years postoperatively. The authors speculated that the lesions detected by low-intensity signal represented fibrous replacement of the normal trabecular bone. Frobell et al. [26] reported that, of 58 subjects who demonstrated bone bruises following ACL rupture, complete resolution occurred in only 22 (38 %) by 1 year post-injury. Theologis and associates [89] conducted a longitudinal analysis of 9 patients with acute ACL injuries with advanced T_{1p} MRI techniques to quantify the volume and signal intensity of bone marrow edema-like lesions. 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_{1p} values compared to surrounding cartilage at all follow-up time periods. Elevated T_{1p} 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.

Fig. 3.3 Bone bruise on MRI following rupture of the ACL

Johnson et al. [37] reported that patients who sustained an ACL rupture and a bone bruise had significantly greater problems in the first 4 weeks after the injury compared to those with an isolated ACL tear. This included larger effusions which took longer to resolve, time to achieve normal gait, time to achieve knee motion equal to the opposite knee, and higher pain scores. The authors suggested that these patients should delay ACL reconstruction and allow a return of homeostasis to decrease postoperative complications.

In another investigation, Johnson and associates [36] biopsied ten knees with acute ACL ruptures and a geographic bone bruise on the lateral femoral condyle. All of the knees had evidence of articular cartilage damage at arthroscopy which ranged from softening to chondral fracture. Degeneration of chondrocytes and necrosis of osteocytes in subchondral bone were observed and were proportional to the amount of cartilage damage documented during surgery.

Other studies have reported that bone bruises resolve with time [27, 29, 30, 78]. Yoon et al. [96], 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–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. [30] 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 % acute ACL rupture, natural history unclear.
- Large severe bone bruises associated with subchondral or osteochondral injuries, may persist for years after injury.
- 6-year follow-up 23 patients: persistent marrow changes on MRI in 65 %.
- 145 patients: bone bruise in >80 % within 3 months, 57 % 3 months–1 year, and 11 % >1 year.
- Consider most severe bone injuries part of sequela of posttraumatic OA.

Biochemical Alterations Following ACL Injury

ACL ruptures create biochemical alterations in the knee joint which have been speculated by many authors to play a role in the development of OA. Higuchi et al. [34] investigated the biochemical characteristics, including the concentrations of cytokines, matrix metalloproteinases (MMPs), and tissue inhibitors of metalloproteinases (TIMP) in synovial fluid in 32 knees 2–134 weeks after ACL injury. The data indicated higher concentrations compared to normal knees of MMP-3 and TIMP-1. These concentrations remained elevated regardless of the amount of time that had elapsed after injury. There was an imbalance between MMP-3 and TIMP-1 which the authors believed could make the knee more susceptible to cartilage deterioration.

Fang and associates [24] studied levels of cartilage oligomeric matrix protein (COMP) in cartilage overlying geographic bone bruises in 13 patients a mean of 7 ± 3.6 weeks following their ACL injury. At arthroscopy, all patients had abnormal lesions varying from softening to chondral fracture. Biopsies indicated chondrocyte necrosis and loss of the proteoglycan component of the matrix and altered tissue distribution in the cartilage. There were significantly higher amounts of approximately ten-fold of COMP in injured knees compared to contralateral knees. In addition, there were significant amounts of degradative COMP fragments in the synovial fluid in the injured knees. These findings were similar to those viewed in cartilage from knees with degenerative OA. The authors hypothesized that the pathologic changes of cartilage adjacent to bone bruises following ACL ruptures may predispose patients for subsequent development of posttraumatic OA regardless of the treatment (conservative or surgical) of the injury.

The trauma of an ACL injury usually activates an acute chemical inflammatory response. Johnson et al. [37] noted that patients with concomitant bone bruises and ACL ruptures had more severe joint effusions than those with isolated ACL injuries (4.6 and 3.9 cm, respectively) and required a longer time to subside (4 weeks versus 2.4 weeks). Cameron and associates [12] obtained 84 samples of synovial fluid from patients with both acute and chronic ACL ruptures and measured the levels of nine cytokines. Two distinct subgroups were noted; those with high levels of two cytokines which are important components of the inflammatory process (interleukin-1 [IL-1] and tumor necrosis factor-α [TNFα]) and those with very low levels. The authors interpreted the results as indicating that some patients are more predisposed to developing OA due to a chronic inflammatory reaction, while others appear to be genetically protected from such a response.

Elsaid and associates [20] detected significantly decreased levels of lubricin, a glycoprotein secreted by the synovial fluid that provides chondroprotective properties to articular cartilage, in the acute time period following ACL injury in 30 patients. The investigators also noted significantly high levels of proinflammatory cytokines compared to the contralateral knee. Namely, interleukin-1 (IL-6) and TNFα remained detectable for nearly 6 months after the injury. The authors concluded that the decrease in lubricin concentrations in the synovial fluid following ACL injury may place the joint at increased risk of degenerative changes.

Lohmander et al. [46] reported that the level of cartilage proteoglycan fragments in synovial fluid following acute ACL ruptures was greatly increased compared to normal knees. In many patients, this elevation was observed up to 4 years after the injury. The authors concluded that the elevated proteoglycan in synovial fluid may be a marker for early posttraumatic arthritis. In another investigation, Lohmander et al. [47] described the release into synovial fluid of soluble molecular fragments specific for the degradation of mature articular cartilage (type II) following ACL injury. The concentrations of cross-linked C-telopeptide fragments of type II collagen were significantly higher ($P < .001$) than those of a control group at all time intervals studied (1–1,000 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.

Tiderius and associates [90] found that ACL injuries initiated a generalized biochemical change that lead to a loss of glycosaminoglycans (GAG) from both the medial and lateral femoral condyle articular cartilage a mean of 3 weeks after the injury. Whether the GAG loss was associated with subsequent OA was unknown. The findings were unrelated to the presence of bone bruises, which occurred in 63 % of the patients in the lateral femoral condyle.

Lee et al. [44] reported increased levels of resistin, a proinflammatory mediator, in patients early after ACL rupture (1 day to 10 weeks). These authors agreed that in some patients, the prolonged inflammatory response to injury may be a prevalent cause of degenerative arthritis. Restin was found to have a direct role in cartilage matrix turnover and breakdown and in the induction of inflammatory cytokines.

In summary, there appears to be substantial upregulation of numerous cytokines following ACL injury which may remain elevated for many months or years afterward. The tibial subluxation that occurs during the injury may cause in many instances a noteworthy impact injury to the articular cartilage and underlying subchondral bone, with subsequent necrosis and early onset of OA. The effect of the biochemical alterations in the knee joint remains unknown and is a subject for future investigations.

Critical Points

- Biochemical alterations in knee after ACL injury may correlate with development of OA.
- Substantial upregulation of cytokines after ACL injury, remain elevated for months or years afterward.
- Synovial fluid analysis 84 knees: some patients predisposed to developing OA due to a chronic inflammatory reaction, others genetically protected from such response.
- Acute ACL ruptures: level of cartilage proteoglycan fragments in synovial fluid greatly increased compared to controls. Integrity type II collagen network compromised soon after injury.

Effects of Meniscectomy in ACL-Reconstructed Knees

Studies have shown that, regardless of the outcome of ACL reconstruction in terms of restoration of knee stability, meniscectomy accelerates degenerative joint changes as previously discussed (Fig. 3.4) [13, 17, 31, 33, 45, 53, 81, 82]. Nakata et al. [53], in a 10-year follow-up of 61 patients who had undergone allograft ACL reconstruction, reported that radiographic OA changes were present in 13 of 15 (87 %) meniscectomized knees compared to 12 of 46 (26 %) knees with intact menisci ($P < .05$). The failure rate of the ACL grafts in this study was 7 %. Cohen et al. [13] found a significant association ($P < .0001$) between meniscectomy and radiographic OA in a group of 62 patients followed 10–15 years after ACL reconstruction. The presence of bilateral meniscal tears was associated with OA in both the medial and lateral tibiofemoral compartments. Hart and associates [31] used both radiographs and SPECT in 31 patients 9–13 years post ACL B-PT-B autograft reconstruction. Using weight-bearing radiographs, the incidence of OA was 13 % in knees with intact menisci and 44 % in knees that had undergone meniscectomy. When considering data from the SPECT scans, the incidence of OA was 7 % in knees with intact

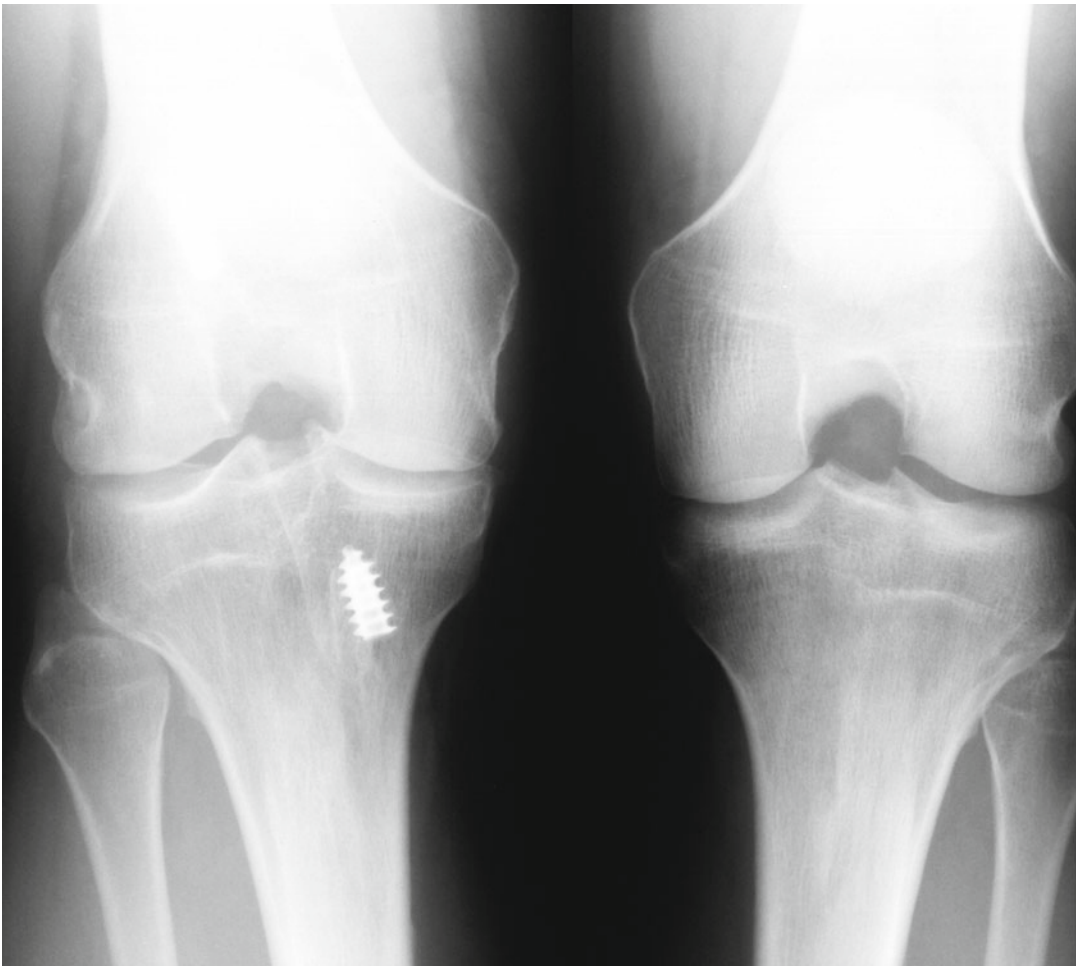


Fig. 3.4 Standing radiographs of a patient 14 years following a right ACL reconstruction and subsequent medial meniscectomy. The pivot-shift test was negative, indicating a stable reconstruction. However, narrowing to the medial tibiofemoral compartment is evident and the patient demonstrated 2° of varus alignment (Reprinted with permission from Noyes and Barber-Westin [67])

menisci and 31 % in knees that had undergone meniscectomy.

Jonsson et al. [39] examined 63 patients 5–9 years following ACL reconstruction with weight-bearing radiographs and scintigraphic bone scans. A significant association was found between meniscectomy and OA on radiographs ($P=.02$). Removal of the medial meniscus did not affect the scintigraphic uptake difference in the medial joint space; however, removal of the lateral meniscus resulted in approximately 60 % high uptake difference in the lateral joint space compared to controls ($P=.0006$). Seventeen patients (27 %) had unstable knees (positive pivot-shift test) which were also associated with increased scintigraphic uptake over the entire knee.

Jomha et al. [38] followed 55 patients 7 years after ACL B-PT-B autograft reconstruction. A significant increase in radiographic OA was detected in meniscectomized knees compared to those with intact menisci ($P<.02$). Medial meniscectomy more strongly correlated ($P<.001$) with OA than lateral meniscectomy ($P<.05$). In addition, meniscectomy correlated with low IKDC scores, as these patients had a 34 % chance of an abnormal or severely abnormal result compared with 14 % of patients with intact menisci.

Diamantopoulos et al. [18] noted a significant increase in radiographic OA in meniscectomized knees that underwent ACL revision reconstruction compared to those with intact menisci ($P<.001$).

In addition, these authors reported significantly higher Lysholm scores in knees with intact menisci ($P < .05$). Salmon et al. [81] reviewed 43 patients 13 years following ACL B-PT-B autograft reconstruction and reported a significant association between poor OA grades and medial meniscectomy ($P = .006$). Patients who had undergone meniscectomy also had increased laxity with time ($P = .03$) and greater odds of graft rupture by a factor of 6 ($P = .05$). ACL graft rupture occurred in 21 % of meniscectomized knees compared to 8 % of those with intact menisci.

Shelbourne and Gray [82] found that meniscectomy significantly impacted the long-term subjective and objective outcome of ACL B-PT-B autograft reconstruction 5–16 years postoperatively. Knees that underwent either medial or lateral meniscectomy had significantly lower subjective Noyes questionnaire scores ($P = .002$). Significantly increased anterior tibial translation on KT-1000 testing was found in patients who had either the medial meniscus or both menisci removed ($P = .006$). The overall IKDC rating was normal or nearly normal in 87 % of knees with both menisci intact, compared to 70 % of lateral meniscectomized knees, 63 % of medial meniscectomized knees, and 60 % of bilateral meniscectomized knees. Radiographic OA was found in 9 % of lateral meniscectomized knees, 23 % of medial meniscectomized knees, and 25 % of bilateral meniscectomized knees compared to just 3 % of knees with intact menisci.

Critical Points

- Meniscectomy accelerates degenerative joint changes regardless of outcome of ACL reconstruction in terms of restoration of knee stability.
- 10-year follow-up 61 patients: radiographic OA 87 % meniscectomized knees, 26 % knees with intact menisci.
- 7-year follow-up 55 patients: meniscectomy correlated with low IKDC scores.
- 13-year follow-up 43 patients: correlation meniscectomy increased laxity with time, ACL graft rupture.

Salvaging Meniscus Tissue

The authors have long advocated repair of meniscus tears instead of resection, assuming the appropriate indications are met to preserve function of this vital structure [11, 58, 62, 67, 70, 79]. Many studies have documented favorable outcomes in knees following meniscus repair compared to meniscectomy [67, 87]. Even so, a recent review of the literature from 2001 to 2011 showed that the majority of meniscus tears are treated with meniscectomy during ACL reconstruction [71]. The review, which encompassed 159 studies and 11,711 meniscus tears, determined that 65 % were treated with meniscectomy; 27 %, with repair; and 9 %, left in situ. The results were concerning because studies have shown that, regardless of knee stability achieved after ACL reconstruction, meniscectomy accelerates degenerative joint changes. The authors' 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, 1 plane: repairable in all cases, high success rates
6. Middle one-third tears: red-white (vascular supply present) or white-white (no blood supply): 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

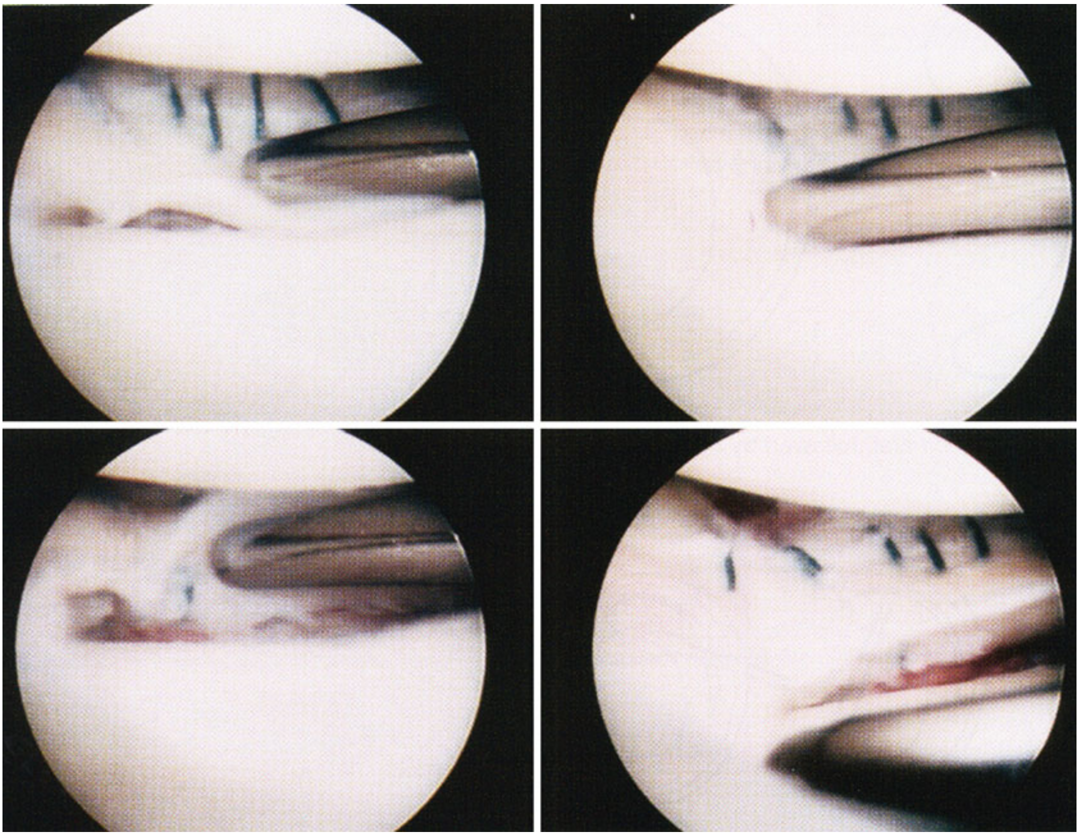


Fig. 3.5 Meniscus repair instead of meniscectomy to preserve knee joint function. A longitudinal meniscal tear site demonstrates some fragmentation inferiorly. This tear required multiple superior and inferior vertical divergent sutures to achieve anatomic reduction (From Noyes and Barber-Westin [62]; with permission from SAGE Publications, Inc.)

in detail elsewhere [67]. The repair uses an accessory posteromedial or posterolateral approach for exposure to tie the sutures using an inside-out suture technique. A meticulous vertically divergent suture technique is favored in which multiple sutures are passed through both the superior and inferior surfaces of the meniscus (Fig. 3.5). The postoperative rehabilitation program allows immediate knee motion and early weight bearing, but protects the repairs by not allowing squatting, kneeling, or running for 4–6 months [32, 72].

The authors have conducted a series of clinical studies to determine the outcome of this operation [11, 58, 62, 69, 79]. In one of the largest cohorts who underwent this procedure reported to date, 198 meniscus repairs were followed 2–9.6 years postoperatively [79]. All of the tears extended into the middle third region, 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 than that compared to patients who underwent meniscus repair for tears in the peripheral region (typically reported to be ≥90 % [67]), the authors believed it justified the repair of tears in the central zone, especially in patients aged 21–40 years and highly competitive athletes.

In another study, the authors followed 30 patients ≥40 years of age who underwent meniscus repair for tears that extended into the middle third region [58]. At follow-up, 2–6 years postoperatively, 87 % had not required further surgery and had no symptoms related to the meniscus repair.

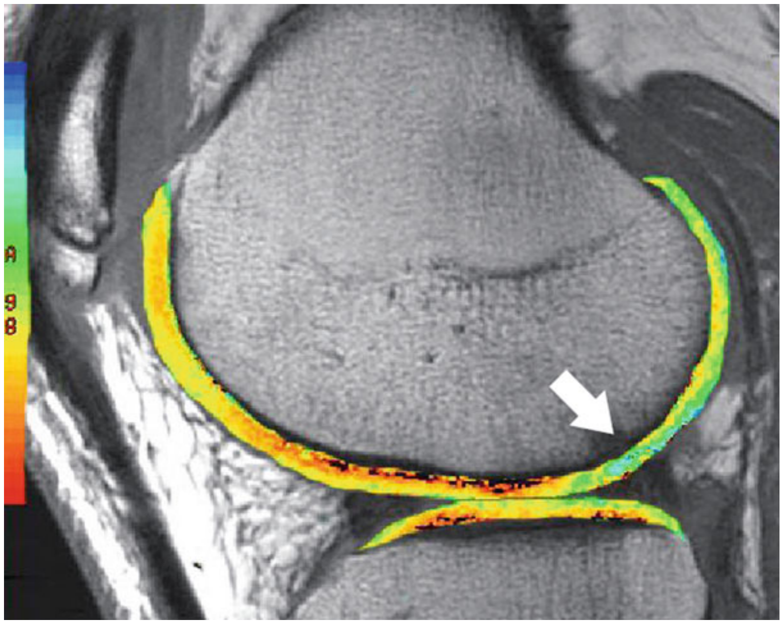


Fig. 3.6 T2 MRI of a 37-year-old male who is 17 years post-ACL reconstruction and lateral meniscus repair. The patient was asymptomatic with light sports activities. The lateral meniscus repair was healed, and the ACL reconstruction restored normal stability. Prolongation of T2 values is noted over the posterior margin with adjacent subchondral sclerosis (*arrow*) (From Noyes et al. [70])

A long-term outcome study of single longitudinal meniscus repairs extending into the central region in patients ≤20 years of age was conducted by the authors [70]. Twenty-nine repairs were evaluated; 18 by follow-up arthroscopy, 19 by clinical evaluation, 17 by MRI, and 22 by weight-bearing posteroanterior radiographs. The follow-up was 10–22 years postoperatively. A 3 Tesla MRI scanner with cartilage-sensitive pulse sequences and T2 mapping was performed. The authors found that 18 (62 %) of the meniscus repairs had normal or nearly normal characteristics. Six repairs (21 %) required arthroscopic resection, 2 had loss of joint space on radiographs, and 3 that were asymptomatic failed according to MRI criteria. There was no significant difference in the mean T2 scores in the menisci that had not failed between the involved and contralateral tibiofemoral compartments. There were no significant differences between the initial and long-term evaluations for pain, swelling, jumping, patient knee condition rating, or the Cincinnati rating score. The majority of patients were participating in sports without problems, which did not affect the failure rate. The outcomes support the recommendation in younger active patients to spend as much time and attention to a meniscus repair as a concurrent ACL reconstruction, as the eventual function of the knee joint is equally dependent on the success of the both structures (Fig. 3.6).

Critical Points

- Authors 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.
- Meticulous vertically 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.

Reinjury and Failure Rates Following ACL Reconstruction: Long-Term Studies

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 (Table 3.3) [2, 3, 19, 33, 35, 38, 41, 50, 53, 74, 81, 83]. Authors have investigated several possible factors to account for reinjuries including young patient age, high sports activity level, prior meniscectomy, and improper graft placement. 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. Since long-term studies report that reinjuries frequently occur over several years after the operation, a minimum of 5–7 years of follow-up provides realistic rates and short-term studies [94] should not be included in this assessment.

Hui et al. [35] examined 90 patients 15 years following isolated, endoscopic ACL B-PT-B 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. Twenty-nine patients sustained either a rupture to the ACL graft (7 patients, 8 %) or to the contralateral ACL (22 patients, 24 %) postoperatively. ACL graft ruptures were associated with vertical graft angle, as patients with a coronal graft inclination angle <17° had ten times greater odds of ACL graft failure ($P = .02$). Contralateral ACL ruptures were associated with age of <18 years, as these patients had seven times greater odds of injury compared to those >18 years old ($P = .001$). The remaining 72 patients had normal or nearly normal ACL graft ratings according to the IKDC system. The authors attributed the high overall rate of reinjury (30 %) to several factors, including inadequate rehabilitation, relative young age of the patients, the high activity level patients returned to after surgery, and vertical graft placement.

Shelbourne et al. [83] reported a 9.6 % overall reinjury rate in a group of 1,415 patients who underwent ACL B-PT-B autograft reconstruction and were followed 5 years postoperatively. The risk of subsequent injury to either knee was 17 % for patients <18 years of age compared to 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 that the reinjuries to the high-risk sports patients had returned to, with basketball and soccer accounting for 67 % of the reinjuries. The mean time to injury was 19 months for the ACL-reconstructed side and 28 months for the contralateral knee.

Pinczewski and associates [74] compared 10-year results of ACL B-PT-B and STG autograft reconstructions in a cohort of 180 knees. There was no significant difference in the incidence of ACL graft rupture between groups. Eight percent of the B-PT-B patients ruptured their ACL graft a mean of 5 years postoperatively, and 13 % of the STG patients ruptured their graft a mean of 4 years postoperatively. ACL graft rupture was associated with increased anterior tibial translation at 2 years postoperatively ($P = .001$). There was a significant difference between groups in the incidence of contralateral ACL rupture, which was associated with age <21 years ($P = .02$). Keays et al. [41] also failed to find a significant difference between patellar tendon and STG autograft ACL reconstructions in the incidence of postoperative reinjuries.

Salmon and associates [81] followed 67 patients who underwent ACL B-PT-B reconstruction 5–13 years postoperatively. The authors included patients who had undergone meniscectomy, but excluded those with concomitant medial collateral ligament ruptures and noteworthy articular cartilage damage. Nine patients (13 %) experienced ACL

Table 3.3 Rates of reinjury to the ACL in reconstructed and contralateral knees in studies with a minimum 5 years of follow-up

Study Level of evidence	Follow-up, years	ACL graft, no.	Failed ACL reconstruction[a]	Injured ACL contralateral knee	Overall ACL reinjury rate for both knees	Factors associated with reinjuries, ACL graft failures
Hui et al. [35]	15	BPTB autograft, 90	7 (8 %)	22 (24 %)	29 (32 %)	Coronal graft inclination angle < 17° (vertical graft placement) for ACL-reconstructed knee
Level IV						Age < 18 year for contralateral knee
Shelbourne et al. [83]	5	BPTB autograft, 1,415	61 (4 %)	75 (5 %)	136 (10 %)	Age < 18 year, participation in basketball or soccer for either knee
Level II						Female gender for contralateral knee
Sajovic et al. [80]	5	BPTB autograft, 30	3 (10 %)	3 (10 %)	6 (20 %)	Not analyzed
Level I		STG autograft, 31	3 (10 %)	2 (6 %)	5 (16 %)	
		Total, 61	6 (10 %)	5 (8 %)	11 (18 %)	
Nakata et al. [53] Level IV	10	Allogeneic-free tendon, 68	7 (10 %)	4 (6 %)	11 (16 %)	Not analyzed
Pinczewski et al. [74]	10	BPTB autograft, 90	7 (8 %)	20 (22 %)	27 (30 %)	Increased laxity for ACL-reconstructed knees
Level II		STG autograft, 90	12 (13 %)	9 (10 %)	21 (23 %)	Age < 21 year for contralateral knee
		Total, 180	19 (11 %)	29 (16 %)	48 (27 %)	
Keays et al. [41]	6	BPTB autograft, 29	0	2 (7 %)	2 (7 %)	Not analyzed
Level II		STG autograft, 27	2 (7 %)	3 (11 %)	5 (18 %)	
		Total, 56	2 (4 %)	5 (9 %)	7 (12 %)	
Salmon et al. [81] Level IV	5–13	BPTB autograft, 67	9 (13 %)	15 (22 %)	24 (36 %)	Age < 21 year, meniscectomy for ACL-reconstructed knee
Drogset et al. [19] Level I	16	BPTB autograft, 42	4 (8 %)	5 (12 %)	9 (21 %)	Not analyzed
Ait Si Selmi et al. [3] Level IV	17	BPTB autograft + iliotibial band extra-articular, 103	40 %	NA	40 %	Not analyzed

Roe et al. [77] Level II	7	BPTB autograft, 90 STG autograft, 90 Total, 180	4 (4 %) 9 (10 %) 13 (7 %)	16 (18 %) 9 (10 %) 25 (14 %)	20 (22 %) 18 (20 %) 38 (21 %)	Not analyzed
Mykelbust et al. [50] Level IV	6–11	BPTB autograft, 57	11 (19 %)	6 (11 %)	17 (30 %)	Return to team handball
Deehan et al. [16] Level II	5	BPTB autograft, 90	3 (3 %)	10 (11 %)	13 (14 %)	Not analyzed

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

graft rupture, and 15 patients (22 %) injured the contralateral ACL. These authors reported that age <21 years increased the odds of a B-PT-B ACL autograft rupture by a factor of 10 and that meniscectomy increased the odds by a factor of 6. Reinjury to the ACL grafts occurred at approximately 6.5 years and to the contralateral knee at approximately 5.5 years postoperatively.

Mykelbust et al. [50] evaluated the effect of return to team handball competition following ACL B-PT-B autograft reconstruction in a group of 57 patients. Fifty patients returned to competition; 11 (22 %) reinjured their ACL-reconstructed knee and 6 (9 %) injured the contralateral knee. There were no further injuries in the players who did not return to handball. The authors reflected that team handball is a high-risk sport; however, other possible reinjury risk factors such as graft placement and rehabilitation were not assessed.

Critical Points

- Long-term failure rates vary widely (3–40 %).
- Factors correlated with ACL graft failure: inadequate rehabilitation, young age, high sports activity level, vertical graft angle, and meniscectomy.
- Contralateral ACL at risk for rupture, higher than ACL graft in some studies (5–24 %).

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. Failure of graft integration, tendon-to-bone healing, or remodeling
3. Lateral, posterolateral, or medial ligament deficiency producing deleterious ACL graft loads
4. Inadequate rehabilitation, failure to address neuromuscular deficiencies in both lower limbs
5. Postoperative infection

Errors in surgical technique are a leading cause of failure of ACL reconstruction [28, 40, 91]. The authors recently reported a series of 122 knees with failed ACL grafts referred to our center for treatment [48]. A nonanatomic graft placement was found in 107 (88 %) knees (Fig. 3.7); 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 %. Aglietti et al. [2] in 1997 described the problem of improper graft placement as a leading issue in ACL B-PT-B autograft failure. In a series of 89 patients followed 5–8 years postoperatively, knees in which the femoral tunnel was misplaced anteriorly had a significantly higher rate of failure compared to knees with a more posterior femoral graft placement (62.5 and 12 %, respectively, $P = .003$). The authors concluded that the anterior tunnel placement could have been the result of inexperience and inadequate visualization of the notch, and that the use of front-entry guides may be a disadvantage.

Problems with endoscopic techniques that lead to improper placement of ACL grafts are now 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 [48, 66, 88]. Trojani et al. [91] 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.

Failure to surgically restore deficient lateral, posterolateral, or medial ligament structures has been noted to cause failure of ACL reconstructions

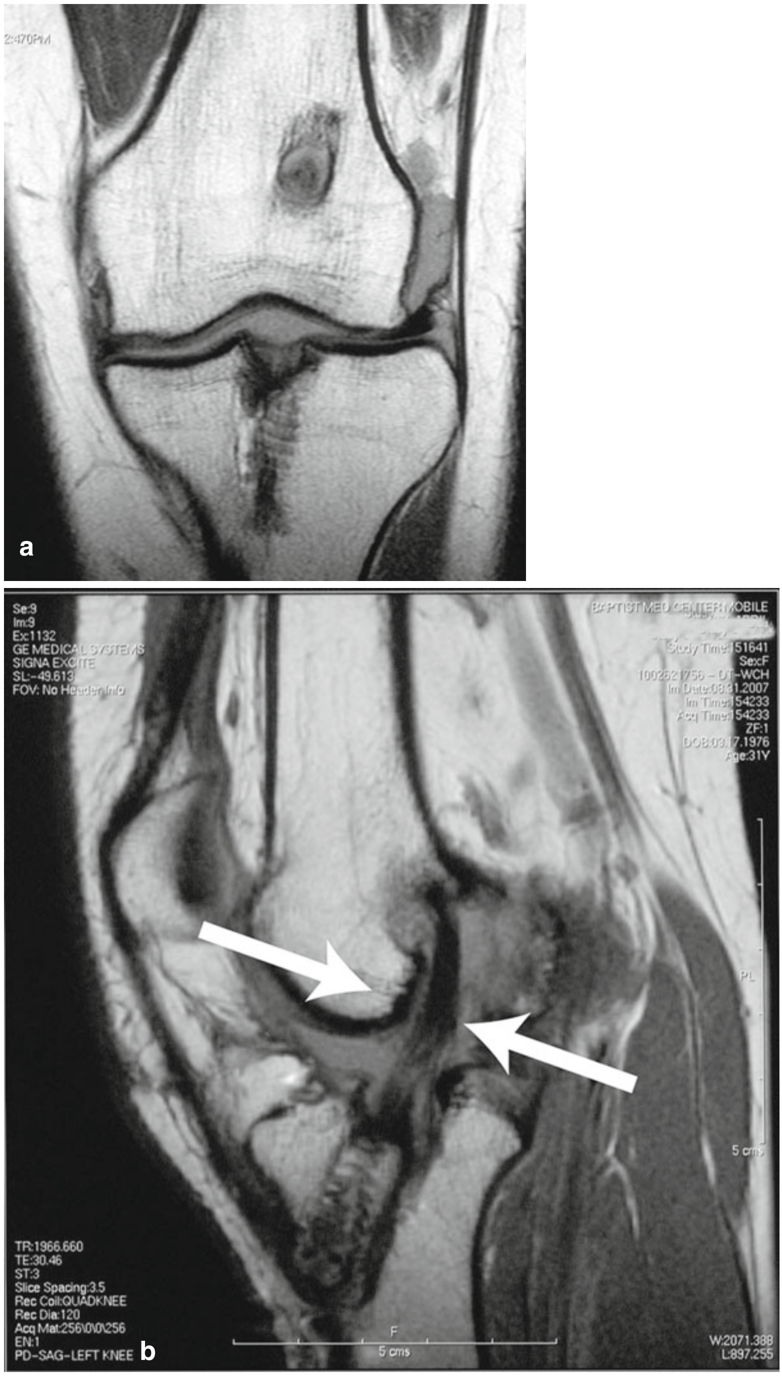


Fig. 3.7 Example of a vertical ACL graft orientation in (**a**) coronal and (**b**) sagittal planes (From Marchant et al. [48]; with permission from SAGE Publications, Inc.)

(Fig. 3.8) [60]. The authors noted that 25 % of 114 consecutive patients requiring ACL revision reconstruction had uncorrected chronic lateral or medial ligament insufficiency [61]. 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. The authors also reported that 14 % of the patients had varus malalignment that had not been corrected before

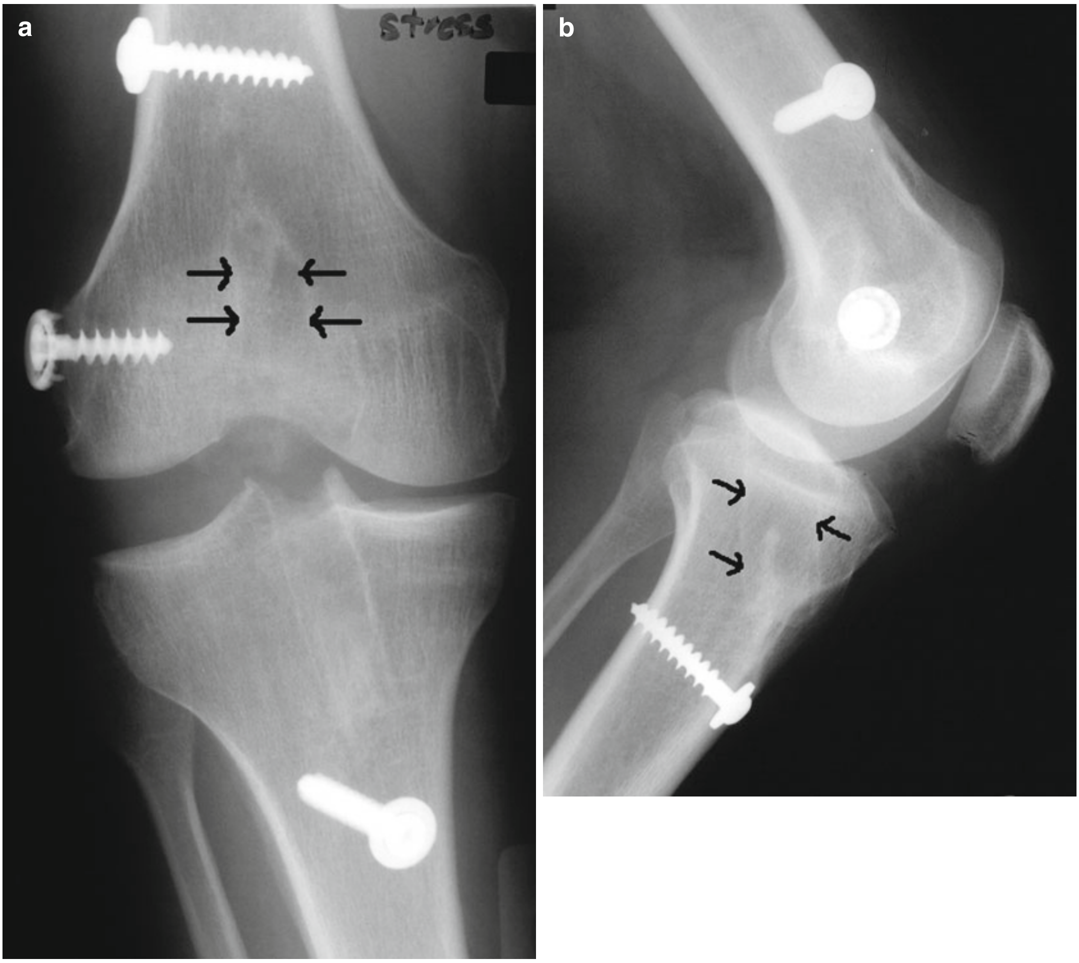


Fig. 3.8 Anteroposterior (**a**) and lateral (**b**) radiographs of a 35-year-old man who presented 5 months after a posterolateral reconstruction with a biceps tendon transfer and an ACL patellar tendon autograft reconstruction for a chronic knee injury. Note the abnormal expansion of both the femoral and tibial tunnels and the vertical orientation of the ACL graft (*arrows*). The patient presented with failure of both the ACL and posterolateral procedures (From Noyes et al. [64]; with permission from SAGE Publications, Inc.)

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 (Figs. 3.9 and 3.10). This is especially true in knees that demonstrate a varus thrust on gait that produces abnormal lateral tibiofemoral joint opening [56, 59] and in triple varus knees with varus recurvatum.

Current ACL reconstruction methods do not reproduce the native ACL or its insertion sites [8]. Tendon-to-bone healing must be accomplished in an environment which produces inferior attachments that may result in suboptimal healing. 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.

Postoperative rehabilitation plays a critical role in returning patients to athletic or demanding occupational activities as safely as possible.

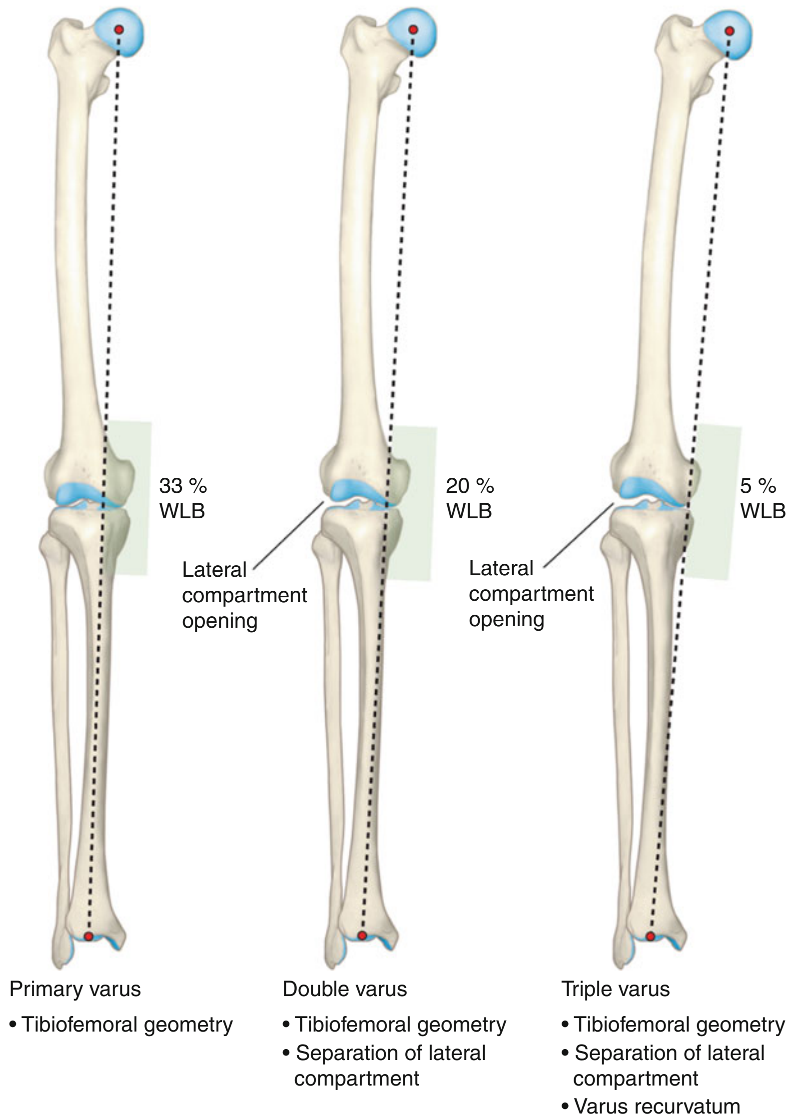


Fig. 3.9 Schematic illustration of primary, double, and triple varus knee angulation. *WBL* weight-bearing line (Reprinted with permission from Noyes and Barber-Westin [65])

The authors recommend return to play programs that include advanced neuromuscular retraining before patients are released to unrestricted athletics [4, 6, 7]. 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 shown in Table 3.3.

Once an ACL reconstruction has failed, the outcome of a revision procedure is usually less desirable than primary ACL reconstruction procedures due to higher failure rates, increased symptoms and functional limitations, and eventual joint arthritis [28, 40, 66]. 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

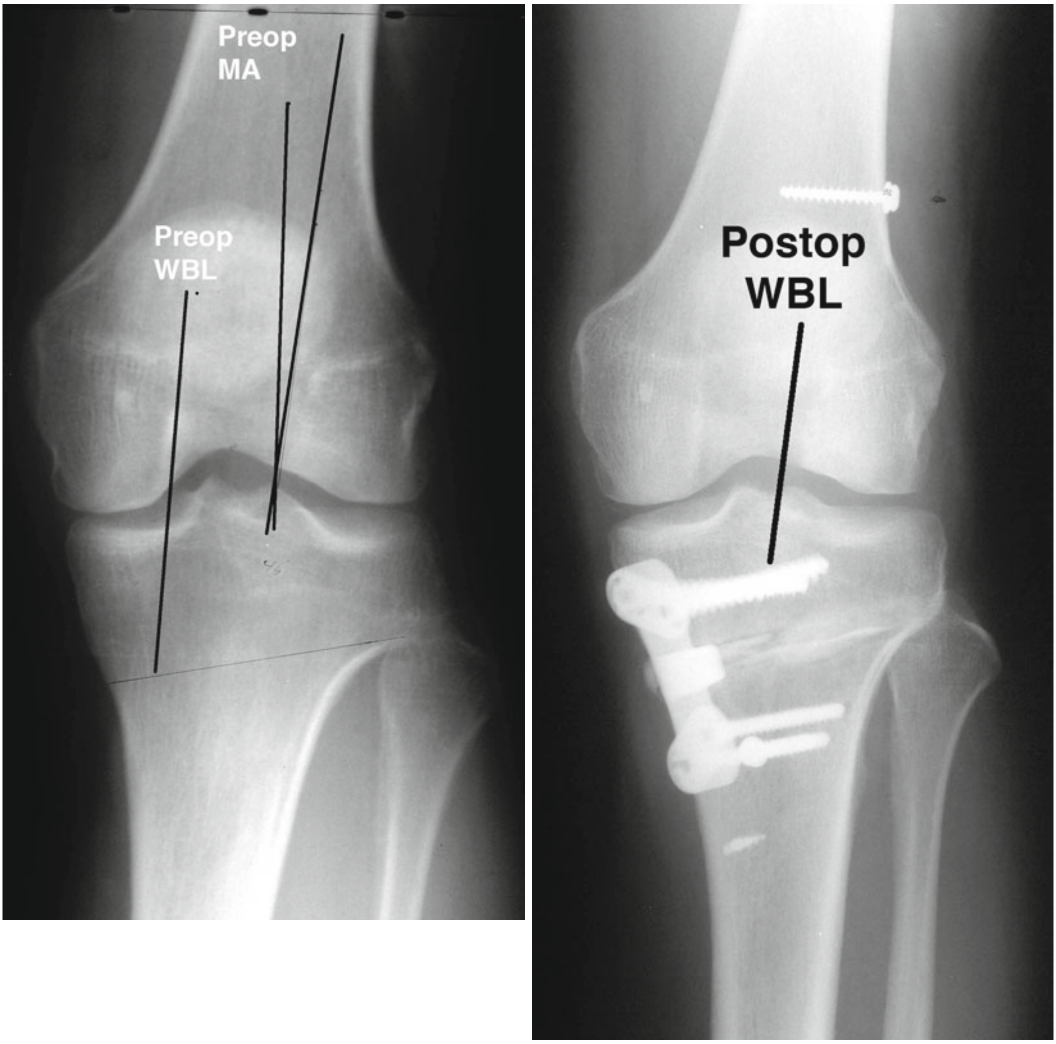


Fig. 3.10 Radiograph on the left shows the weight-bearing line (18 %) and mechanical axis in a varus-angulated, ACL-deficient knee. The patient underwent an opening wedge tibial osteotomy and ACL STG reconstruction. The radiograph on the right shows the corrected weight-bearing line after surgery of 52 % (Reprinted with permission from Noyes and Barber-Westin [65])

(see Chap. 2). The authors' studies [60, 61] 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 [66] following primary operations. For instance, the authors reported in a study involving 30 patients who received an ACL B-PT-B 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 [57]. In comparison, in a study of 55 patients who received a revision ACL B-PT-B autograft [60], 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 deficiency.
- Inadequate rehabilitation.
- Postoperative infection.

References

1. Adalberth T, Roos H, Lauren M et al (1997) Magnetic resonance imaging, scintigrapy, and arthroscopic evaluation of traumatic hemarthrosis of the knee. Am J Sports Med 25(2):231–237
2. Aglietti P, Buzzi R, Giron F (1997) Arthroscopic-assisted anterior cruciate ligament reconstruction with the central third patellar tendon. A 5–8-year follow-up. Knee Surg Sports Traumatol Arthrosc 5(3):138–144
3. Ait Si Selmi T, Fithian D, Neyret P (2006) The evolution of osteoarthritis in 103 patients with ACL reconstruction at 17 years follow-up. Knee 13(5):353–358
4. Barber-Westin SD, Heckmann TP, Noyes FR (2009) Scientific basis of rehabilitation after anterior cruciate ligament autogenous reconstruction. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 268–305
5. Barber-Westin SD, Hermeto AA, Noyes FR (2010) A 6-week neuromuscular training program for competitive junior tennis players. J Strength Cond Res 24(9):2372–2382
6. Barber-Westin SD, Noyes FR (2011) Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. Arthroscopy 27(12):1697–1705
7. Barber-Westin SD, Noyes FR (2011) Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. Phys Sportsmed 39(3):100–110
8. Bedi A, Rodeo SA (2009) Biology of anterior cruciate ligament graft healing. In: Noyes FR (ed) Noyes knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 117–129
9. Beynnon BD, Johnson RJ, Abate JA et al (2005) Treatment of anterior cruciate ligament injuries, part I. Am J Sports Med 33(10):1579–1602
10. Beynnon BD, Uh BS, Johnson RJ et al (2005) Rehabilitation after anterior cruciate ligament reconstruction. A prospective, randomized, double-blind comparison of programs administered over 2 different time periods. Am J Sports Med 33(3):347–359
11. Buseck MS, Noyes FR (1991) Arthroscopic evaluation of meniscal repairs after anterior cruciate ligament reconstruction and immediate motion. Am J Sports Med 19(5):489–494
12. Cameron ML, Fu FH, Paessler HH et al (1994) Synovial fluid cytokine concentrations as possible prognostic indicators in the ACL-deficient knee. Knee Surg Sports Traumatol Arthrosc 2(1):38–44
13. Cohen M, Amaro JT, Ejnisman B et al (2007) Anterior cruciate ligament reconstruction after 10 to 15 years: association between meniscectomy and osteoarthrosis. Arthroscopy 23(6):629–634
14. Costa-Paz M, Muscolo DL, Ayerza M et al (2001) Magnetic resonance imaging follow-up study of bone bruises associated with anterior cruciate ligament ruptures. Arthroscopy 17(5):445–449
15. Davies NH, Niall D, King LJ et al (2004) Magnetic resonance imaging of bone bruising in the acutely injured knee – short-term outcome. Clin Radiol 59(5):439–445
16. Deehan DJ, Salmon LJ, Webb VJ et al (2000) Endoscopic reconstruction of the anterior cruciate ligament with an ipsilateral patellar tendon autograft. J Bone Joint Surg 82-B(7):984–991
17. Diamantopoulos A, Tokis A, Tzurbakis M et al (2005) The posterolateral corner of the knee: evaluation under microsurgical dissection. Arthroscopy 21(7): 826–833
18. Diamantopoulos AP, Lorbach O, Paessler HH (2008) Anterior cruciate ligament revision reconstruction: results in 107 patients. Am J Sports Med 36(5): 851–860
19. Drogset JO, Grontvedt T, Robak OR et al (2006) A sixteen-year follow-up of three operative techniques for the treatment of acute ruptures of the anterior cruciate ligament. J Bone Joint Surg Am 88(5):944–952
20. Elsaid KA, Fleming BC, Oksendahl HL et al (2008) Decreased lubricin concentrations and markers of joint inflammation in the synovial fluid of patients with anterior cruciate ligament injury. Arthritis Rheum 58(6):1707–1715
21. Engebretsen L, Arendt E, Fritts HM (1993) Osteochondral lesions and cruciate ligament injuries. MRI in 18 knees. Acta Orthop Scand 64(4):434–436
22. Even-Sapir E, Arbel R, Lerman H et al (2002) Bone injury associated with anterior cruciate ligament and meniscal tears: assessment with bone single photon emission computed tomography. Invest Radiol 37(9):521–527
23. Faber KJ, Dill JR, Amendola A et al (1999) Occult osteochondral lesions after anterior cruciate ligament rupture. Six-year magnetic resonance imaging follow-up study. Am J Sports Med 27(4):489–494
24. Fang C, Johnson D, Leslie MP et al (2001) Tissue distribution and measurement of cartilage oligomeric matrix protein in patients with magnetic resonance imaging-detected bone bruises after acute anterior cruciate ligament tears. J Orthop Res 19(4):634–641
25. Fink C, Hoser C, Hackl W et al (2001) Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture – is sports activity a determining variable? Int J Sports Med 22(4):304–309
26. Frobell RB, Le Graverand MP, Buck R et al (2009) The acutely ACL injured knee assessed by MRI: changes in joint fluid, bone marrow lesions, and cartilage during the first year. Osteoarthritis Cartilage 17(2):161–167

27. Frobell RB (2011) Change in cartilage thickness, posttraumatic bone marrow lesions, and joint fluid volumes after acute ACL disruption: a two-year prospective MRI study of sixty-one subjects. J Bone Joint Surg Am 93(12):1096–1103
28. George MS, Dunn WR, Spindler KP (2006) Current concepts review: revision anterior cruciate ligament reconstruction. Am J Sports Med 34(12):2026–2037
29. Graf BK, Cook DA, De Smet AA et al (1993) "Bone bruises" on magnetic resonance imaging evaluation of anterior cruciate ligament injuries. Am J Sports Med 21(2):220–223
30. Hanypsiak BT, Spindler KP, Rothrock CR et al (2008) Twelve-year follow-up on anterior cruciate ligament reconstruction: long-term outcomes of prospectively studied osseous and articular injuries. Am J Sports Med 36(4):671–677
31. Hart AJ, Buscombe J, Malone A et al (2005) Assessment of osteoarthritis after reconstruction of the anterior cruciate ligament: a study using single-photon emission computed tomography at ten years. J Bone Joint Surg Br 87(11):1483–1487
32. Heckmann TP, Noyes FR, Barber-Westin SD (2009) Rehabilitation of meniscus repair and transplantation procedures. In: Noyes FR, Barber-Westin SD (eds) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 806–817
33. Hertel P, Behrend H, Cierpinski T et al (2005) ACL reconstruction using bone-patellar tendon-bone press-fit fixation: 10-year clinical results. Knee Surg Sports Traumatol Arthrosc 13(4):248–255
34. Higuchi H, Shirakura K, Kimura M et al (2006) Changes in biochemical parameters after anterior cruciate ligament injury. Int Orthop 30(1):43–47
35. Hui C, Salmon LJ, Kok A et al (2011) Fifteen-year outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft for "isolated" anterior cruciate ligament tear. Am J Sports Med 39(1):89–98
36. Johnson DL, Urban WP, Caborn DNM et al (1998) Articular cartilage changes seen with magnetic resonance imaging-detected bone bruises associated with acute anterior cruciate ligament rupture. Am J Sports Med 26(3):409–414
37. Johnson KL, Bealle DP, Brand JC et al (2000) The effect of a geographic lateral bone bruise on knee inflammation after acute anterior cruciate ligament rupture. Am J Sports Med 28(2):152–155
38. Jomha NM, Pinczewski LA, Clingeleffer A et al (1999) Arthroscopic reconstruction of the anterior cruciate ligament with patellar-tendon autograft and interference screw fixation. The results at seven years. J Bone Joint Surg Br 81(5):775–779
39. Jonsson H, Riklund-Ahlstrom K, Lind J (2004) Positive pivot shift after ACL reconstruction predicts later osteoarthrosis: 63 patients followed 5–9 years after surgery. Acta Orthop Scand 75(5):594–599
40. Kamath GV, Redfern JC, Greis PE et al (2011) Revision anterior cruciate ligament reconstruction. Am J Sports Med 39(1):199–217
41. Keays SL, Bullock-Saxton JE, Keays AC et al (2007) A 6-year follow-up of the effect of graft site on strength, stability, range of motion, function, and joint degeneration after anterior cruciate ligament reconstruction: patellar tendon versus semitendinosus and Gracilis tendon graft. Am J Sports Med 35(5):729–739
42. Kessler MA, Behrend H, Henz S et al (2008) Function, osteoarthritis and activity after ACL-rupture: 11 years follow-up results of conservative versus reconstructive treatment. Knee Surg Sports Traumatol Arthrosc 16(5):442–448
43. Lahm A, Erggelet C, Steinwachs M et al (1998) Articular and osseous lesions in recent ligament tears: arthroscopic changes compared with magnetic resonance imaging findings. Arthroscopy 14(6):597–604
44. Lee JH, Ort T, Ma K et al (2009) Resistin is elevated following traumatic joint injury and causes matrix degradation and release of inflammatory cytokines from articular cartilage in vitro. Osteoarthritis Cartilage 17(5):613–620
45. Li RT, Lorenz S, Xu Y et al (2011) Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. Am J Sports Med 39(12): 2595–2603
46. Lohmander LS, Saxne T, Heinegard DK (1994) Release of cartilage oligomeric matrix protein (COMP) into joint fluid after knee injury and in osteoarthritis. Ann Rheum Dis 53(1):8–13
47. Lohmander LS, Atley LM, Pietka TA et al (2003) The release of crosslinked peptides from type II collagen into human synovial fluid is increased soon after joint injury and in osteoarthritis. Arthritis Rheum 48(11): 3130–3139
48. Marchant BG, Noyes FR, Barber-Westin SD et al (2010) Prevalence of nonanatomical graft placement in a series of failed anterior cruciate ligament reconstructions. Am J Sports Med 38(10):1987–1996
49. Mihelic R, Jurdana H, Jotanovic Z et al (2011) Long-term results of anterior cruciate ligament reconstruction: a comparison with non-operative treatment with a follow-up of 17–20 years. Int Orthop 35(7): 1093–1097
50. Myklebust G, Holm I, Maehlum S et al (2003) Clinical, functional, and radiologic outcome in team handball players 6 to 11 years after anterior cruciate ligament injury: a follow-up study. Am J Sports Med 31(6):981–989
51. Myklebust G, Bahr R (2005) Return to play guidelines after anterior cruciate ligament surgery. Br J Sports Med 39(3):127–131
52. Nakamae A, Engebretsen L, Bahr R et al (2006) Natural history of bone bruises after acute knee injury: clinical outcome and histopathological findings. Knee Surg Sports Traumatol Arthrosc 14(12):1252–1258
53. Nakata K, Shino K, Horibe S et al (2008) Arthroscopic anterior cruciate ligament reconstruction using fresh-frozen bone plug-free allogeneic tendons: 10-year follow-up. Arthroscopy 24(3):285–291
54. Nishimori M, Deie M, Adachi N et al (2008) Articular cartilage injury of the posterior lateral tibial plateau

associated with acute anterior cruciate ligament injury. Knee Surg Sports Traumatol Arthrosc 16(3):270–274
55. Noyes FR, Bassett RW, Grood ES (1980) Arthroscopy in acute traumatic hemarthrosis of the knee. Incidence of anterior cruciate tears and other injuries. J Bone Joint Surg Am 62(5):687–695, 757
56. Noyes FR, Barber SD, Simon R (1993) High tibial osteotomy and ligament reconstruction in varus angulated, anterior cruciate ligament-deficient knees. A two- to seven-year follow-up study. Am J Sports Med 21(1):2–12
57. Noyes FR, Barber-Westin SD (1997) A comparison of results in acute and chronic anterior cruciate ligament ruptures of arthroscopically assisted autogenous patellar tendon reconstruction. Am J Sports Med 25(4):460–471
58. Noyes FR, Barber-Westin SD (2000) Arthroscopic repair of meniscus tears extending into the avascular zone with or without anterior cruciate ligament reconstruction in patients 40 years of age and older. Arthroscopy 16(8):822–829
59. Noyes FR, Barber-Westin SD, Hewett TE (2000) High tibial osteotomy and ligament reconstruction for varus angulated anterior cruciate ligament-deficient knees. Am J Sports Med 28(3):282–296
60. Noyes FR, Barber-Westin SD (2001) Revision anterior cruciate surgery with use of bone-patellar tendon-bone autogenous grafts. J Bone Joint Surg Am 83-A(8):1131–1143
61. Noyes FR, Barber-Westin SD (2001) Revision anterior cruciate ligament reconstruction: report of 11-year experience and results in 114 consecutive patients. Instr Course Lect 50:451–461
62. 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
63. Noyes FR, Barber-Westin SD (2006) Anterior cruciate ligament revision reconstruction: results using a quadriceps tendon-patellar bone autograft. Am J Sports Med 34(4):553–564
64. 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
65. Noyes FR, Barber-Westin SD (2009) Primary, double, and triple varus knee syndromes: diagnosis, osteotomy techniques, and clinical outcomes. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 821–895
66. Noyes FR, Barber-Westin SD (2009) Anterior cruciate ligament primary and revision reconstruction: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 140–228
67. Noyes FR, Barber-Westin SD (2009) Meniscus tears: diagnosis, repair techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 733–771
68. Noyes FR, Grood ES (2009) Knee ligament function and failure. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 89–113
69. Noyes FR, Barber-Westin SD (2010) Management of special problems associated with knee menisci: repair of complex and avascular tears and meniscus transplantation. In: Egol KA (ed) Instructional course lectures, vol 60. AAOS, Rosemont
70. 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
71. Noyes FR, Barber-Westin SD (2012) Treatment of meniscus tears during anterior cruciate ligament reconstruction. Arthroscopy 28(1):123–130
72. Noyes FR, Heckmann TP, Barber-Westin SD (2012) Meniscus repair and transplantation: a comprehensive update. J Orthop Sports Phys Ther 42(3):274–290
73. O'Neill DB (2001) Arthroscopically assisted reconstruction of the anterior cruciate ligament. A follow-up report. J Bone Joint Surg Am 83-A(9): 1329–1332
74. Pinczewski LA, Lyman J, Salmon LJ et al (2007) A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: a controlled, prospective trial. Am J Sports Med 35(4):564–574
75. Potter HG (2011) Commentary on an article by Richard B. Frobell, PhD: change in cartilage thickness, posttraumatic bone marrow lesions, and joint fluid volumes after acute acl disruption. a two-year prospective MRI study of sixty-one subjects. J Bone Joint Surg Am 93(12):e71 (71–72)
76. Potter HG, Jain SK, Ma Y et al (2012) Cartilage injury after acute, isolated anterior cruciate ligament tear: immediate and longitudinal effect with clinical/MRI follow-up. Am J Sports Med 40(2):276–285
77. Roe J, Pinczewski LA, Russell VJ et al (2005) A 7-year follow-up of patellar tendon and hamstring tendon grafts for arthroscopic anterior cruciate ligament reconstruction: differences and similarities. Am J Sports Med 33(9):1337–1345
78. Rosen MA, Jackson DW, Berger PE (1991) Occult osseous lesions documented by magnetic resonance imaging associated with anterior cruciate ligament ruptures. Arthroscopy 7(1):45–51
79. Rubman MH, Noyes FR, Barber-Westin SD (1998) Arthroscopic repair of meniscal tears that extend into the avascular zone. A review of 198 single and complex tears. Am J Sports Med 26(1):87–95
80. Sajovic M, Strahovnik A, Komadina R et al (2008) The effect of graft choice on functional outcome in anterior cruciate ligament reconstruction. Int Orthop 32(4):473–478
81. Salmon LJ, Russell VJ, Refshauge K et al (2006) Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft:

minimum 13-year review. Am J Sports Med 34(5): 721–732
82. Shelbourne KD, Gray T (2000) Results of anterior cruciate ligament reconstruction based on meniscus and articular cartilage status at the time of surgery. Five- to fifteen-year evaluations. Am J Sports Med 28(4):446–452
83. Shelbourne KD, Gray T, Haro M (2009) Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med 37(2):246–251
84. Speer KP, Spritzer CE, Bassett FH et al (1992) Osseous injury associated with acute tears of the anterior cruciate ligament. Am J Sports Med 20(4): 382–389
85. Spindler KP, Schils JP, Bergfeld JA et al (1993) Prospective study of osseous, articular, and meniscal lesions in recent anterior cruciate ligament tears by magnetic resonance imaging and arthroscopy. Am J Sports Med 21(4):551–557
86. Stein LN, Fischer DA, Fritts HM et al (1995) Occult osseous lesions associated with anterior cruciate ligament tears. Clin Orthop Relat Res 313:187–193
87. Stein T, Mehling AP, Welsch F et al (2010) Long-term outcome after arthroscopic meniscal repair versus arthroscopic partial meniscectomy for traumatic meniscal tears. Am J Sports Med 38(8):1542–1548
88. Stevenson WW 3rd, Johnson DL (2007) "Vertical grafts": a common reason for functional failure after ACL reconstruction. Orthopedics 30(3):206–209
89. Theologis AA, Kuo D, Cheng J et al (2011) Evaluation of bone bruises and associated cartilage in anterior cruciate ligament-injured and -reconstructed knees using quantitative t(1rho) magnetic resonance imaging: 1-year cohort study. Arthroscopy 27(1):65–76
90. Tiderius CJ, Olsson LE, Nyquist F et al (2005) Cartilage glycosaminoglycan loss in the acute phase after an anterior cruciate ligament injury: delayed gadolinium-enhanced magnetic resonance imaging of cartilage and synovial fluid analysis. Arthritis Rheum 52(1):120–127
91. Trojani C, Sbihi A, Djian P et al (2010) Causes for failure of ACL reconstruction and influence of meniscectomies after revision. Knee Surg Sports Traumatol Arthrosc 19(2):196–201
92. Vellet AD, Marks PH, Fowler PJ et al (1991) Occult posttraumatic osteochondral lesions of the knee: prevalence, classification, and short-term sequelae evaluated with MR imaging. Radiology 178(1): 271–276
93. von Porat A, Roos EM, Roos H (2004) High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. Ann Rheum Dis 63(3):269–273
94. Wright RW, Dunn WR, Amendola A et al (2007) Risk of tearing the intact anterior cruciate ligament in the contralateral knee and rupturing the anterior cruciate ligament graft during the first 2 years after anterior cruciate ligament reconstruction: a prospective MOON cohort study. Am J Sports Med 35(7): 1131–1134
95. Wu WH, Hackett T, Richmond JC (2002) Effects of meniscal and articular surface status on knee stability, function, and symptoms after anterior cruciate ligament reconstruction: a long-term prospective study. Am J Sports Med 30(6):845–850
96. Yoon JP, Chang CB, Yoo JH et al (2010) Correlation of magnetic resonance imaging findings with the chronicity of an anterior cruciate ligament tear. J Bone Joint Surg Am 92(2):353–360
97. Yoon KH, Yoo JH, Kim KI (2011) Bone contusion and associated meniscal and medial collateral ligament injury in patients with anterior cruciate ligament rupture. J Bone Joint Surg Am 93A(16): 1510–1518

Part III

Proposed Risk Factors of Noncontact ACL Injuries

Role of Shoe–Surface Interaction and Noncontact ACL Injuries

4

Ariel V. Dowling and Thomas P. Andriacchi

Contents

A.V. Dowling, Ph.D. (✉)
Department of Mechanical Engineering,
Stanford University, Durand Building 061,
Stanford CA, 94305-4308, USA
e-mail: adowling@stanford.edu

T.P. Andriacchi, Ph.D.
Department of Mechanical Engineering,
Stanford University,
Stanford, CA, USA

Department of Orthopedic Surgery,
Stanford University Medical Center,
Durand Building 227,
Stanford, CA 94305-4308, USA

Bone and Joint Center,
Palo Alto VA,
Palo Alto, CA, USA
e-mail: tandriac@stanford.edu

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:

$$F_{\text{friction}} = \mu^* F_{\text{normal}}$$

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.

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_4, © Springer-Verlag Berlin Heidelberg 2012

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.

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 [17, 22, 24–27, 31, 33, 39]. 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 her movement techniques in specific ways that may increase the 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.

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 vs. soccer cleats vs. 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. 4.1, cleats A and B), soccer cleats (Fig. 4.1, cleats D and E; Fig. 4.2, flat cleats; Fig. 4.3, cleats A and B), and turf cleats (Fig. 4.3, 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.

Cleat Characteristics: Number, Diameter, and 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

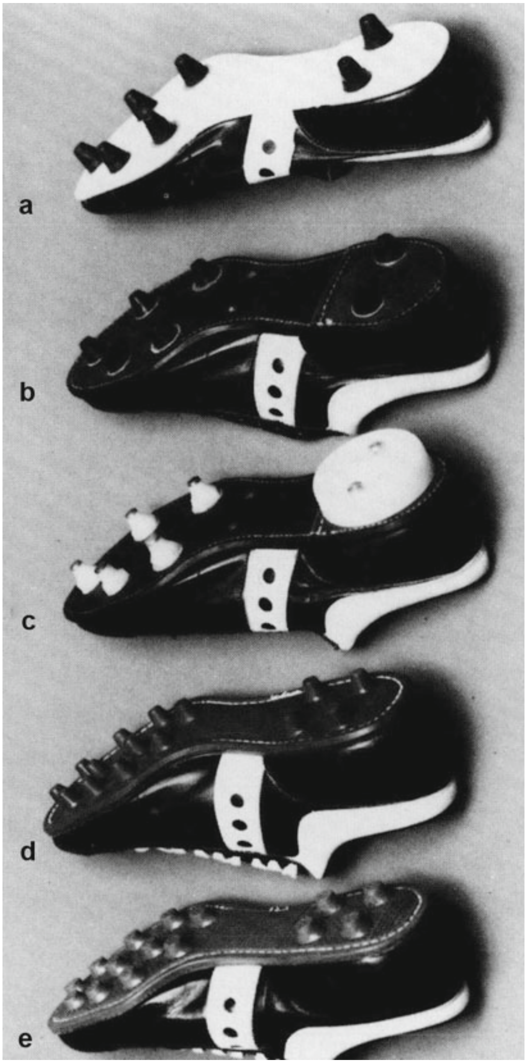


Fig. 4.1 Cleat models tested by Torg et al. [39] (**a**) Group I prototype; conventional 7-posted football shoe with 3/4" cleats. (**b**) Group II prototype; conventional 7-posted football shoe with 1/2" cleats. (**c**) Group III prototype; conventional football shoe with Bowdoin heel and five 3/4" cleats. (**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. [39]; with permission of SAGE Publications, Inc.)

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 7–11 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 of injury. In 1971, Torg and Quedenfeld [38] conducted one of the first major studies that investigated the relationship between cleat characteristics and injury rates. Differences in knee injury rates on natural grass were found 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 [38]. 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 was because these shoes created a higher COF with the playing surface, especially in rotational movements. In a set of experiments, Torg et al. [39] 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,

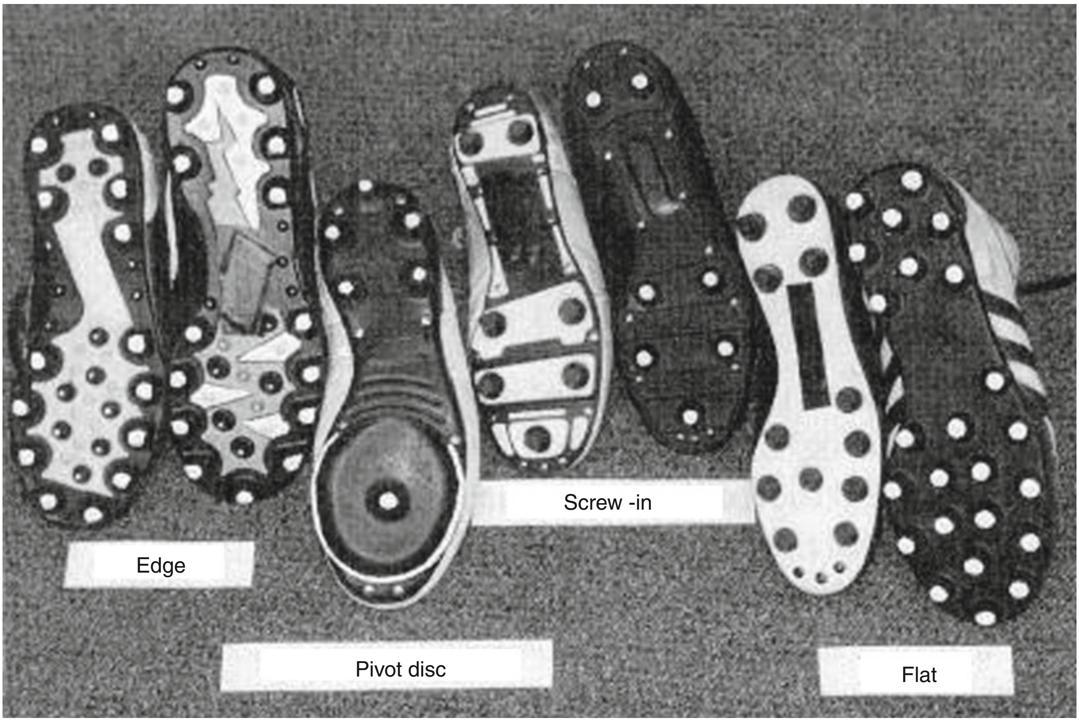


Fig. 4.2 Cleat models tested by Lambson et al. [17] Four American football cleat designs evaluated for torsional resistance and rate of ACL injuries (Reprinted from Lambson et al. [17]; with permission of SAGE Publications, Inc.)

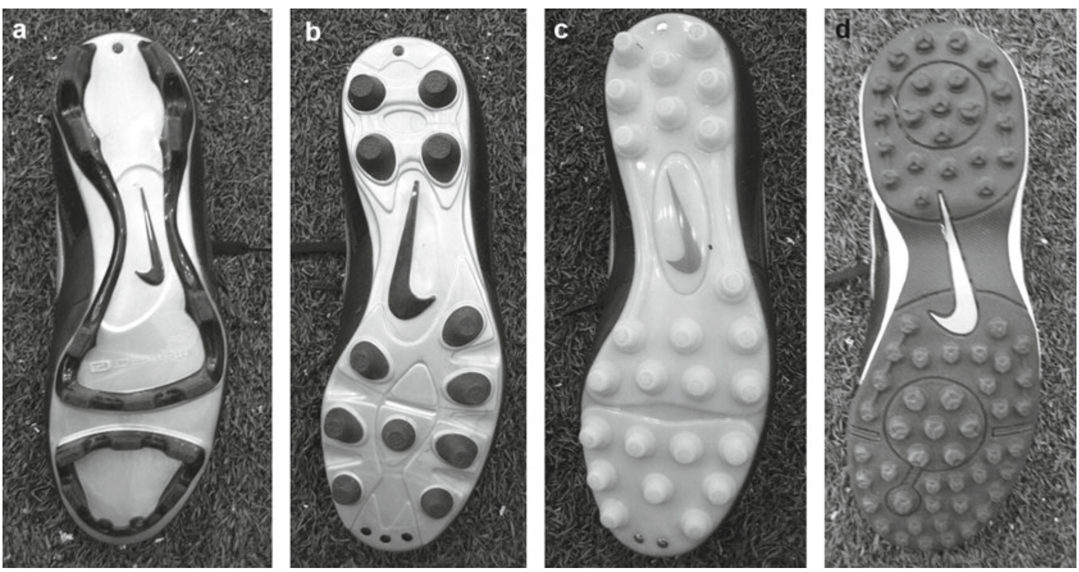


Fig. 4.3 Cleat models tested by Queen et al. [32] Configurations of the four Nike Vitoria cleat types: (**a**) bladed, (**b**) firm ground, (**c**) hard ground, and (**d**) turf cleat (Reprinted from Queen et al. [32]; with permission of BMJ Publishing Group Ltd.)

and (E) soccer cleats with 3/8" length and 1/2" diameter cleats (Fig. 4.1). 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 became more numerous, shorter, and wider, the release coefficient (and therefore the COF) required to release the shoe–surface interaction decreased. 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 [38] for players wearing American football cleats was most likely a result of increased COF created by the cleats.

These results were confirmed in a later study by Heidt et al. [12], who also determined that peak rotational torque decreased as the cleats became 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 N m), followed by soccer cleats (31.0 N m), turf cleats (14.1 N m), and court shoes (11.8 N m). In a separate study by Villwock et al. [41], 10 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 N m) when compared to the rest of the cleat groups (Table 4.1). This investigation showed that turf cleats, which have numerous very short cleats, had a lower COF for the shoe–surface interaction.

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. [17] conducted a 3-year prospective study to evaluate how the torsional resistance and the incidence of ACL injury varied based on cleat placement in 3,000 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 seven 0.5" long cleats; and (4) pivot disk cleats, with a 10-cm circular disk centered around one cleat on the forefoot (Fig. 4.2) [17]. 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 created a higher COF of the shoe–surface interaction [17]. This result was confirmed by Villwock et al. [41], 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 created a higher COF with the surface and were also associated with an increased rate of ACL injury.

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. [38, 39] 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.

Table 4.1 Mean peak torques (N m) for ten cleated football shoe models tested on four playing surfaces [41]

	12-studded		Edge			Hybrid		7-studded		Turf	Mean ± SD across surfaces
Surface	Blade II	7 fly	Vapor	TRX	Blitz	Superbad	Grid Iron	Blade D	Quickslant	Turf Hog	
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^	

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)

SD standard deviation

*Significant difference from natural grass surfaces ($P < .001$)

**Significant difference from all other surfaces ($P = .008$)

^Significant difference from all other shoe models ($P < .001$)

Furthermore, most of the studies have focused on comparing different cleat models. Since the 7-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 are similar in terms of cleat characteristics, and many women use men's cleats for sports. More research needs to be conducted to accurately determine the effects of cleat characteristics on female athletes.

Critical Points

- Cleats are the most common form of footwear during ACL injurious sports.
- Primary cleat characteristics: number, diameter, 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 was conducted using male athletes but may apply to female athletes.

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. 4.4).

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

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 [26]. 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. 4.5) in the Bermuda (couch) grass increased the "trapping" of the athletes' cleats, thereby increasing the COF between the grass and the shoe [26]. 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.

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. 4.6). These fields were coarse and could cause significant friction burns and

Fig. 4.4 Team handball played on an artificial rubberized floor. Reprinted by permission of user Ahodges7 [45]

blisters for the players [34]. 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 [34]. 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. 4.7 [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 [34]. The combination of sand and rubber provided stability and elasticity, which allowed athletes wearing cleats to "dig" into the surface for traction (Fig. 4.8). The most recent fourth generation artificial turf contained improvements such as different mixes of infill materials, long (up to 80 mm) and soft fibers, and variable fiber density [34]. 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 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 were comparable between third and fourth generation artificial turf surfaces and natural grass [4, 43, 44].

Fig. 4.5 Grass varieties tested by Orchard et al. [26] (**a**) Bermuda (couch) grass surface, showing thick thatch layer between grass leaves and soil. (**b**) Kikuyu grass, also showing thick thatch layer. (**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 [26]; with permission of BMJ Publishing Group Ltd.)

Fig. 4.6 First generation artificial turf. 10–12-mm fiber length, integral shock pad, nylon, unfilled, hard, and abrasive. Developed in the 1960s [34] (Reprinted by permission of Loughborough University)

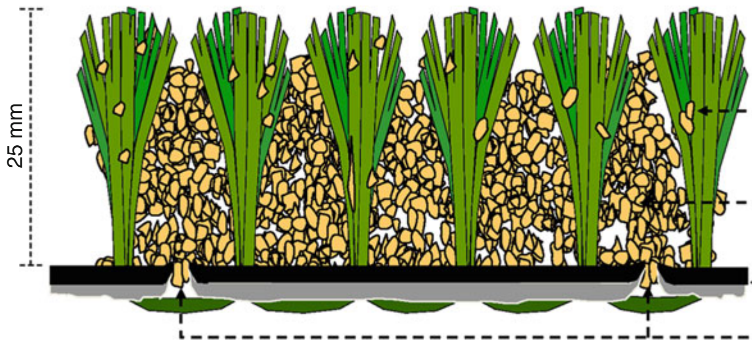


Fig. 4.7 Second generation artificial turf. 20–35-mm fiber length, monofilament or fibrillated polypropylene, wider spaced tufts, and rounded sand infill [14]. Developed in the late 1970s, initially without a shock pad. Banned in the 1980s by United Kingdom professional soccer for being unplayable [34] (Reprinted by permission of Taylor & Francis)

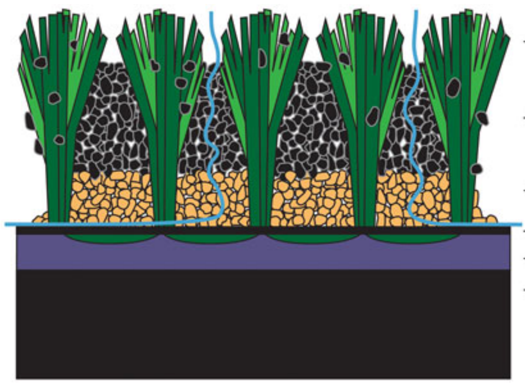


Fig. 4.8 Third generation artificial turf. 40–65 mm fiber length (long pile), monofilament/fibrillated fibers, with sand/rubber infill. Developed in the late 1990s [34] (Reprinted by permission of Sheehan)

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 nine-year study (1980–1989) of injury rates in the National Football League (NFL) found a significantly higher ACL injury rate on AstroTurf (first generation, 36 out of 48 injuries) compared to natural grass (12 out of 48 injuries) for special teams play for special teams play; the authors concluded that 50% of the ACL injuries that occurred on the AstroTurf could be directly attibuted to that playing surface [31]. In 1988, Nigg and Segesser [21] 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 natural grass in American football. Furthermore, in 1990, Skovron et al. [35] 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 [2]. Arnason et al. 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) [13].

Unfortunately, few studies have been conducted on the effects of first and second

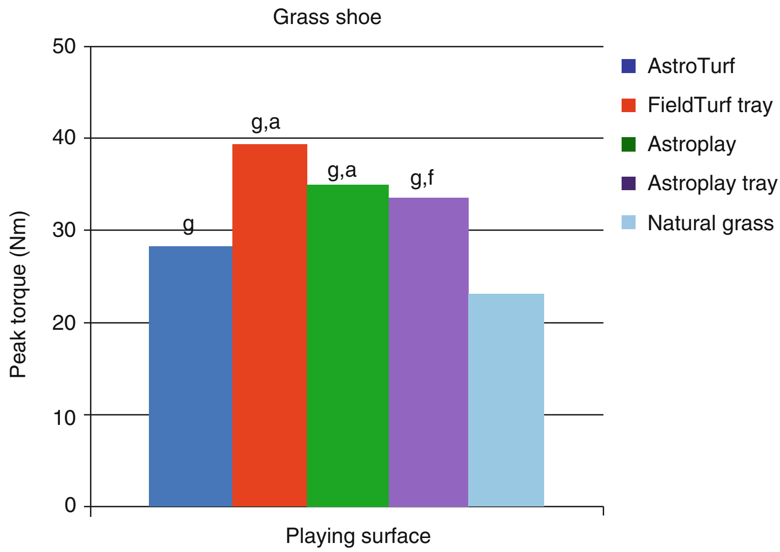


Fig. 4.9 Mean peak torques for the grass shoe across all playing surfaces under a compression load of 333 N; g signifies a significant difference from natural grass; a signifies a significant difference from AstroTurf, and f signifies a significant difference from FieldTurf tray [18]

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 [15]. 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 [24]. Lambson et al. [17] 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. [18] 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. 4.9). For the turf shoe, the peak torque on the AstroTurf and FieldTurf was greater than the natural grass (Fig. 4.10) [18]. These results were confirmed by Villwock et al. [41], 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 torque (118.3 N m), followed by FieldTurf (111.8 N m) and the natural grass surfaces (94.9 N m and 83.1 N m). 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. [39] compared the release coefficients for various cleat models on three types of first and second generation artificial surfaces: AstroTurf, Tartan Turf, and Poly-turf. 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. [12] 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 N m vs. 23.56 N m). Differences in methodology, testing

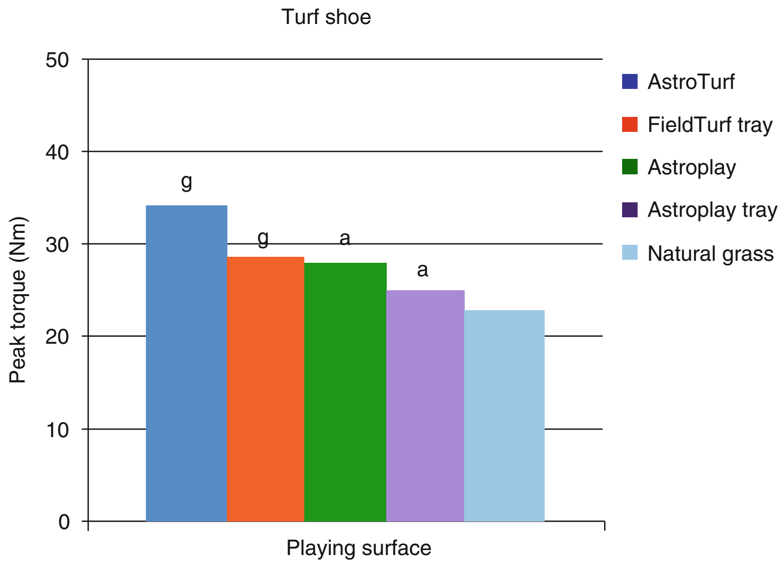


Fig. 4.10 Mean peak torques for the turf shoe across all playing surfaces under a compression load of 333 N; g signifies indicated a significant difference from natural grass; a signifies a significant difference from AstroTurf, and f signifies a significant difference from FieldTurf tray [18]

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 [5]. 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 AstroTurf produced not only greater rotational torque but also increased intra-articular pressure at the knee when compared to natural grass.

Third and Fourth Generation Turf

More recent studies of third and fourth generation artificial turf have observed that the rates of knee injuries were comparable between these surfaces and natural grass [43]. In two prospective studies, FieldTurf (third generation) was associated with similar overall rates of injury for American high school football players [19] and collegiate football players during game situations [20]. Elite European soccer players also exhibited similar injury rates between third generation artificial turf and natural grass during the 2002–2003 season [7].

Injury rates of female athletes on third and fourth generation artificial turf have also been reported. Steffen et al. [37] conducted an investigation on 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 injuries) was not large enough for statistical significance. Another extensive study by Fuller et al. [9, 10] 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 1,000 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 [9]. During practices, the incidence of injury (per 1,000 player-hours) was 0.02 for artificial turf and 0.09 for grass [10].

Other studies on male and female youth players have yielded similar results for newer generations of artificial turf. Soligard et al. [36] studied injury rates among youth soccer players in Norway from 2005–2008. 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 1,000 player-hours) was 4.6 on artificial turf and 5.6 on grass. Aoki et al. [1] 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 in the section "Artificial Turf" suggest that some surfaces may be similar to grass, while others may be similar to older generations of artificial turf. Livesay et al. [18] 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. 4.9). For the turf cleats, only FieldTurf had greater peak rotational torque than grass, and Astroplay had less peak rotational torque than AstroTurf (Fig. 4.10). Villwock et al. [41] determined that for the 15 cleat models tested, FieldTurf had less peak rotational torque than AstroTurf, but more peak rotational torque than two different natural grass surfaces (Table 4.1). 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.

Artificial Rubberized 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 [30]. 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 [30]. 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 [29].

Female athletes may also have a greater risk for ACL injury on rubberized flooring than male athletes. From 1989–2000, Olsen et al. [22] 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 (0.96/1,000 player-hours) on the artificial rubberized floor versus 8 (0.41/1,000 player-hours) on the wood floor, which was statistically significant ($P = .03$). For men, there was no significant difference in the incidence rate for rubberized versus wood floor (0.20/1000 and 0.32/1,000 player-hours, respectively). This study concluded that the ACL injury rate for females was more than twofold higher on the artificial rubberized floors than on the wooden floors, indicating that the risk for injury on rubberized floors is disproportionately greater for women. Furthermore, Pasanen et al. [27] 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 on the artificial rubberized floor was 5.0/1000 player-hours compared to 2.1/1000 player-hours 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 [3, 8]. 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 high and may be the cause of the observed increase in ACL injury among female athletes on this surface.

Critical Points

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

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. [37] 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 rubberized 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 rubberized floors. Until then, female athletes should exercise caution when competing on this surface.

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.

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 on the Australian football league from 1989–1993 found that 92.5 % of the observed ACL injuries occurred during dry conditions as opposed to wet conditions [33]. A subsequent study on Australian football from 1992–1999 by Orchard et al. [23] 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 semi-professional 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) [11].

Analyses of different surfaces during both wet and dry conditions have confirmed that the dry conditions created a higher COF of the shoe–surface interaction. Torg et al. in 1974 [39] 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. [12] 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 N m and 17.4 N m, 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.

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. [25] of NFL American football games from 1989–1998, 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 was that the domes were insulated from the weather conditions, so temperature extremes did not change the ambient environment of the domes. 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 began in the fall and extended through the winter [24]. 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. [25] confirmed these results, as the incidence of ACL injury decreased in the later, 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 [24].

In the laboratory, it has been shown that the temperature of the shoe–surface interaction affected the release coefficient on AstroTurf; specifically, the release coefficient increased as the temperature increased [40]. Five shoe models (2 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 showed that higher temperature resulted in an increased COF of the shoe–surface interaction, suggesting that this was the cause of the greater incidence of ACL injury observed in hot conditions.

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 the surface, temperature of the shoe–surface interaction) can affect the incidence ACL injury.
- Dry conditions (low rainfall, high evaporation) result in an increased incidence ACL injury and increased COF compared to wet conditions.
- Warm conditions (hot weather) result in an 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.

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 encountered a high COF shoe–surface interaction, they altered their movement techniques in order to accommodate the change in the COF. The movement alterations led to changes in the athlete's biomechanics that increased their risk for ACL injury. These biomechanical changes may be the reason for the observed increase in ACL injury rates with high COF. As described in Part III, specific kinematic and kinetic risk factors have been identified that increased the risk of ACL injury in female athletes. Two of the most critical risk factors were 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 (see Chap. 1). According to the previous research, when the COF of the shoe–surface interaction was increased, athletes decreased their knee flexion angle and increased their knee loading during cutting tasks, thereby also increasing their risk for ACL injury.

Knee Flexion Angle

As described in Part III, female athletes that exhibited a decreased knee flexion angle during cutting movements were at greater risk for suffering an ACL injury. Previous research has also shown that healthy subjects decreased their knee flexion angle during a cutting task when they experienced a high COF shoe–surface interaction, thus increasing their risk of injury. In a study by Dowling et al. [3], 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. 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 adopted as a result of the high COF.

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 (see Part III). Prior research has indicated that healthy subjects increased their knee loading during a cutting task when they experienced a high COF shoe–surface interaction, thus increasing their risk of injury. Wannop et al. [42] conducted a study on knee loading in healthy athletes during the stance phase of a 45° cutting maneuver (Fig. 4.11). 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 N m and 16.12 N m, respectively). Then, a comparison was performed on the athletes' knee loading during the cutting task by shoe type. When wearing the tread shoe (higher COF compared to the smooth shoe), the athletes exhibited significantly higher peak external knee valgus (224.0 N m for the tread shoe vs. 186.8 N m for the smooth shoe) and internal rotation moments (36.23 N m for the tread shoe vs. 32.02 N m for the smooth shoe) [42]. Furthermore, Dowling et al. [3] 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 adopted as a result of the high COF.

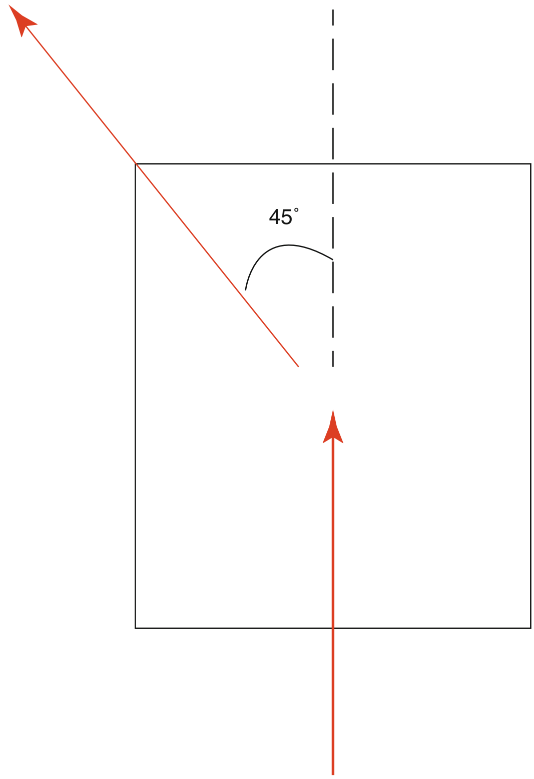


Fig. 4.11 Diagram of the 45° cutting movement performed on the sample track surface adhered to the force platform [42] (Reprinted from Wannop et al. [42]; with permission of SAGE Publications, Inc.)

One study [16] did determine that varying the cleat model during running and cutting tasks did not affect the 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.

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 adopted biomechanical changes as a result of high COF that increased their risk for ACL injury.
- High COF shoe–surface interaction caused decreased knee flexion angle during cutting maneuvers (risk factor for ACL injury).
- High COF shoe–surface interaction caused 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 is required.

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 led to an increase in the incidence of ACL injury (Tables 4.2 and 4.3), especially for female athletes. This increase in injury rates was most likely a result of the athletes' biomechanical adaptations to the high COF, such as decreased knee flexion angle and increased knee loading, that placed 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 [28]. Furthermore, Ekstrand and Nigg [6] have suggested that the guiding principal 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 [39]. 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. The COF of the playing surface can be easily controlled because these surfaces are installed and maintained by

Table 4.2 Studies assessing environmental factors and the incidence of ACL injuries in female athletes

Study	Population	Exposures	Playing surface	ACL injury rate
Pasanen et al. [27]	Top-level Finnish female floorball	Artificial 601	Wooden	Wooden 2.1/1,000 exposures
	1 season	Wooden 971	Artificial rubberized floor	Artificial 5.0/1,000 exposures
Fuller et al. [9]	Collegiate soccer NCAA Injury Surveillance System, 2005–2006	Turf 7,195 men 6,997 women	Synthetic infill artificial turf	Turf 0.42/1,000 exposures: men 1.29/1,000 exposures: women ($P=.09$)
	Match injuries	Grass 27,803 men 37,258 women	Natural grass	Grass 0.47/1,000 exposures: men 1.64/1,000 exposures: women ($P<.01$)
Fuller et al. [10]	Collegiate soccer NCAA Injury Surveillance System, 2005–2006	Turf 56,504 men 46,998 women	Synthetic infill artificial turf	Turf 0.02/1,000 exposures: men 0.02/1,000 exposures: women
	Training injuries	Grass 208,842 men 233,498 women	Natural grass	Grass 0.03/1,000 exposures: men 0.09/1,000 exposures: women
Steffan et al. [37]	Norwegian female soccer	Grass 73,044	Natural grass	Overall 0.08/1,000 exposures
	Aged ≤ 16 years	Turf 39.979	3rd generation artificial turf	3 on grass, 4 on turf, 2 on gravel, 2 indoor floor
	2005 season	Gravel 25,156	Gravel	
		Indoor 4,542	Indoor floor	Only 6 noncontact ACL injuries, limited statistical power

(continued)

Table 4.2 (continued)

Study	Population	Exposures	Playing surface	ACL injury rate
Olsen et al. [22]	Norwegian team handball	37,114 men 57,022 women	Wooden	Wooden 0.41/1,000 exposures: women 0.32/1,000 exposures: men
	Aged 17–33 years 1989–2000		Artificial rubberized floor	Artificial 0.96/1,000 exposures: women ($P = .03$ compared to wooden) 0.20/1,000 exposures: men ($P = .001$ compared to women)

NCAA National Collegiate Athletic Association (USA)

Table 4.3 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 [31]	American pro football 1980–1989	Not given	Natural grasses AstroTurf	No difference overall incidence ACL injuries Special teams only Grass: 12/48 AstroTurf: 36/48
Lambson et al. [17]	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 = .0066)
Ekstrand et al. [7]	492 Elite European soccer Aged 16–39 years 2003–2004	116,744	Natural grasses 3rd generation artificial turf	"Knee sprains" – no difference in incidence between grass and turf Did not provide data for ACL injuries
Orchard et al. [26]	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 [19]	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 [25]	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. [21]	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 1,000 exposures Significant risk factors: history prior ACL injury, low rainfall, 1st grade match, increased height

NFL National Football League (USA)

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 on 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 [24], 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.

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 Part IV, 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 tradeoff 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 USA 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 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 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 match their chosen footwear to the playing surface, e.g., wearing soccer cleats for natural 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 can teach them how to compensate for a high COF shoe–surface interaction without putting themselves at risk for ACL injury. All of these recommendations may help female athletes decrease their risk for ACL injury due to a high COF shoe–surface interaction.

Critical Points

- Further research is required to determine the threshold for maximum COF that optimizes athletic performance while minimizing risk for ACL injury.
- Once this threshold is identified, regulations should limit cleat 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 female athletes to decrease their risk for ACL injury due to a high COF shoe–surface interaction.

References

1. Aoki H, Kohno T, Fujiya H et al (2010) Incidence of injury among adolescent soccer players: a comparative study of artificial and natural grass turfs. Clin J Sport Med 20(1):1–7
2. Arnason A, Gudmundsson A, Dahl HA et al (1996) Soccer injuries in Iceland. Scand J Med Sci Sports 6(1):40–45
3. Dowling AV, Corazza S, Chaudhari AM et al (2010) Shoe-surface friction influences movement strategies during a sidestep cutting task: implications for anterior cruciate ligament injury risk. Am J Sports Med 38(3):478–485
4. Dragoo JL, Braun HJ (2010) The effect of playing surface on injury rate: a review of the current literature. Sports Med 40(11):981–990
5. Drakos MC, Hillstrom H, Voos JE et al (2010) The effect of the shoe–surface interface in the development of anterior cruciate ligament strain. J Biomech Eng 132(1):011003
6. Ekstrand J, Nigg BM (1989) Surface-related injuries in soccer. Sports Med 8(1):56–62
7. Ekstrand J, Timpka T, Hagglund M (2006) Risk of injury in elite football played on artificial turf versus natural grass: a prospective two-cohort study. Br J Sports Med 40(12):975–980
8. Elbert G (1998) The physics hyperbook: friction. http://physics.info/. Accessed on 15 Feb 2012
9. Fuller CW, Dick RW, Corlette J et al (2007) Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 1: match injuries. Br J Sports Med 41(Suppl 1):i20–i26
10. Fuller CW, Dick RW, Corlette J et al (2007) Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 2: training injuries. Br J Sports Med 41(Suppl 1):i27–i32
11. Gabbett T, Minbashian A, Finch C (2007) Influence of environmental and ground conditions on injury risk in rugby league. J Sci Med Sport 10(4):211–218
12. Heidt RS Jr, Dormer SG, Cawley PW et al (1996) Differences in friction and torsional resistance in athletic shoe-turf surface interfaces. Am J Sports Med 24(6):834–842
13. Hoff GL, Martin TA (1986) Outdoor and indoor soccer: injuries among youth players. Am J Sports Med 14(3):231–233
14. James IT, Mcleod AJ (2010) The effect of maintenance on the performance of sand-filled synthetic turf surfaces. Sports Technol 3(1):43–51
15. Jamison S, Lee C (1989) The incidence of female hockey injuries on grass and synthetic playing surfaces. Aust J Sci Med Sport 21(2):15–17
16. Kaila R (2007) Influence of modern studded and bladed soccer boots and sidestep cutting on knee loading during match play conditions. Am J Sports Med 35(9):1528–1536
17. Lambson RB, Barnhill BS, Higgins RW (1996) Football cleat design and its effect on anterior cruciate ligament injuries. A three-year prospective study. Am J Sports Med 24(2):155–159
18. Livesay GA, Reda DR, Nauman EA (2006) Peak torque and rotational stiffness developed at the shoe-surface interface: the effect of shoe type and playing surface. Am J Sports Med 34(3):415–422
19. Meyers MC, Barnhill BS (2004) Incidence, causes, and severity of high school football injuries on FieldTurf versus natural grass: a 5-year prospective study. Am J Sports Med 32(7):1626–1638
20. Meyers MC (2010) Incidence, mechanisms, and severity of game-related college football injuries on FieldTurf versus natural grass: a 3-year prospective study. Am J Sports Med 38(4):687–697
21. Nigg BM, Segesser B (1988) The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries. Sports Med 5(6):375–385
22. Olsen OE, Myklebust G, Engebretsen L et al (2003) Relationship between floor type and risk of ACL injury in team handball. Scand J Med Sci Sports 13(5):299–304
23. Orchard J (2002) Is there a relationship between ground and climatic conditions and injuries in football? Sports Med 32(7):419–432
24. Orchard JW, Chivers I, Aldous D et al (2005) Rye grass is associated with fewer non-contact anterior cruciate ligament injuries than Bermuda grass. Br J Sports Med 39(10):704–709
25. Orchard JW, Powell JW (2003) Risk of knee and ankle sprains under various weather conditions in American football. Med Sci Sports Exerc 35(7):1118–1123

26. Orchard J, Seward H, McGivern J et al (2001) Intrinsic and extrinsic risk factors for anterior cruciate ligament injury in Australian footballers. Am J Sports Med 29(2):196–200
27. Pasanen K, Parkkari J, Rossi L et al (2008) Artificial playing surface increases the injury risk in pivoting indoor sports: a prospective one-season follow-up study in Finnish female floorball. Br J Sports Med 42(3):194–197
28. Pedroza A, Fernandez S, Heidt R Jr et al (2010) Evaluation of the shoe-surface interaction using an agility maneuver. Med Sci Sports Exerc 42(9):1754–1759
29. Pope RP (2002) Rubber matting on an obstacle course causes anterior cruciate ligament ruptures and its removal eliminates them. Mil Med 167(4):355–358
30. Pope RP (2002) Injury surveillance and systematic investigation identify a rubber matting hazard for anterior cruciate ligament rupture on an obstacle course. Mil Med 167(4):359–362
31. Powell JW, Schootman M (1992) A multivariate risk analysis of selected playing surfaces in the National Football League: 1980 to 1989. An epidemiologic study of knee injuries. Am J Sports Med 20(6):686–694
32. Queen RM, Charnock BL, Garrett WE Jr et al (2008) A comparison of cleat types during two football-specific tasks on FieldTurf. Br J Sports Med 42(4):278–284; discussion 284
33. Scranton PE Jr, Whitesel JP, Powell JW et al (1997) A review of selected noncontact anterior cruciate ligament injuries in the National Football League. Foot Ankle Int 18(12):772–776
34. Sheehan B (2011) Artificial grass for sport. Bindweld plastics and Bigprint. www.dpcd.vic.gov.au/_data/assets/pdf_file/0007/58912/ArtificialGrassForSportGuide.pdf. Accessed on 15 Feb 2012
35. Skovron ML, Levy IM, Agel J (1990) Living with artificial grass: a knowledge update. Part 2: epidemiology. Am J Sports Med 18(5):510–513
36. Soligard T, Bahr R, Andersen TE (2012) Injury risk on artificial turf and grass in youth tournament football. Scand J Med Sci Sports. 2012 Jun;22(3):356–361. doi: 10.1111/j.1600-0838.2010.01174.x. Epub 2010 Aug 24
37. Steffen K, Andersen TE, Bahr R (2007) Risk of injury on artificial turf and natural grass in young female football players. Br J Sports Med 41(Suppl 1):i33–i37
38. Torg JS, Quedenfeld T (1971) Effect of shoe type and cleat length on incidence and severity of knee injuries among high school football players. Res Q 42(2): 203–211
39. Torg JS, Quedenfeld TC, Landau S (1974) The shoe-surface interface and its relationship to football knee injuries. J Sports Med 2(5):261–269
40. Torg JS, Stilwell G, Rogers K (1996) The effect of ambient temperature on the shoe-surface interface release coefficient. Am J Sports Med 24(1):79–82
41. Villwock MR, Meyer EG, Powell JW et al (2009) Football playing surface and shoe design affect rotational traction. Am J Sports Med 37(3): 518–525
42. Wannop JW, Worobets JT, Stefanyshyn DJ (2010) Footwear traction and lower extremity joint loading. Am J Sports Med 38(6):1221–1228
43. Williams S, Hume PA, Kara S (2011) A review of football injuries on third and fourth generation artificial turfs compared with natural turf. Sports Med 41(11):903–923
44. Wright JM, Webner D (2010) Playing field issues in sports medicine. Curr Sports Med Rep 9(3): 129–133
45. Ahodges7 from http://en.wikipedia.org/wiki/File:Team_Handball_Jumpshot_09_USA_Nationals.JPG

Neuromuscular Differences Between Men and Women

5

Timothy C. Sell and Scott M. Lephart

Contents

T.C. Sell, Ph.D., P.T. (✉) • S.M. Lephart, Ph.D., A.T.C.
Department of Sports Medicine and Nutrition, University of Pittsburgh, 4044 Forbes Tower, Pittsburgh, PA 15260, USA
e-mail: tcs15@pitt.edu; lephart@pitt.edu

Introduction

Dynamic joint stability is essential to safe and injury-free participation in sports, recreational activities, and exercise. This is particularly true for the knee because many activities place significant biomechanical demands on the lower extremity. Common athletic tasks such as a stop-jump require athletes to perform the maneuver under joint loading forces that approach four times the individual's body weight. Without adequate dynamic knee stability, athletes would be unable to endure these high joint loading forces and sustain ligament injuries [21, 62, 76]. Broadly defined, stability is the state of remaining unchanged in the presence of forces that would normally change the state or condition [120]. From a physics perspective, stability may be compared to static equilibrium in 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) [64]. Joint stability may be defined as the state of a joint remaining or promptly returning to proper alignment through an equalization of forces [96]. It is a complex process that requires synergy between bones, joint capsules, ligaments, muscles, tendons, and sensory receptors [114].

The components of joint stability may be classified as either static or the dynamic. The static components include the ligaments, joint capsule, cartilage, friction, and the bony geometry of the joint [46, 65]. These components are usually measured with joint stress testing and

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_5, © Springer-Verlag Berlin Heidelberg 2012

commonly define clinical joint stability [96]. They 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 during demanding tasks such as running, jumping, and cutting. The static components of joint stability work synergistically with the dynamic components, which include the neuromuscular control of the skeletal muscles crossing the joint [96].

In order to maintain or restore functional joint stability, unconscious activation of the dynamic restraints occurs in preparation for, and in response to, joint motion and loading [96]. This represents a complex interaction between components of the nervous system and the musculoskeletal system that is performed through two control systems, termed feedback and feed-forward [31]. In the feedback control system, sensors continually measure the parameter of interest based on an optimal value. Any change from this optimal value initiates an error signal to which the system triggers a compensatory response.

In a similar manner, the feed-forward system also measures a parameter; however, the measurement occurs intermittently and not continuously. The sensory components of this system measure a potential disturbance or change in the parameter of interest. Once detected, an error signal is elicited and the system responds by issuing commands to counteract the anticipated effects of the disturbance. The commands are largely shaped by previous experiences with similar disturbances. In essence, feed-forward control systems are anticipatory, whereas feedback control systems are characterized by responses only to current stimulus. Both systems are believed to be essential for optimal maintenance of dynamic knee stability.

The majority of research on anterior cruciate ligament (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 [112]. Recently, there has been a shift in this focus to account for the ACL's role relative to rotational stability (internal/external rotation [IR/ER] of the tibia on the femur) [4, 11, 71]. In cadaver studies, the ACL acts a primary restraint to anterior tibial translation and secondary restraint to both valgus/varus and IR/ER loading [17, 70]. Additional data that demonstrates the importance of the ACL in rotational stability includes the effect of injury on in vivo knee kinematics [5, 117, 118]. Using a dynamic stereo x-ray system, Tashman and colleagues [117] demonstrated that there is approximately 10° of knee IR/ER during running. After ACL injury, knee IR/ER range of motion and kinematics are altered [5, 118]. These altered kinematics may be associated with changes in the mechanical restraints that were previously provided by the ACL.

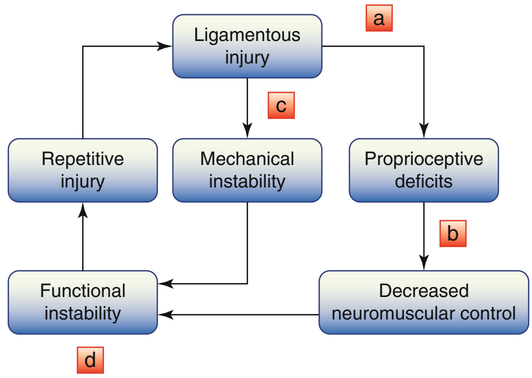


Fig. 5.1 Functional joint stability paradigm

The functional joint stability paradigm (Fig. 5.1) was developed to demonstrate the effects of injury, surgery, rehabilitation, and injury prevention on joint stability [56, 60]. As originally described, the precipitating event (initiating factor) is a ligament injury. This injury has a significant effect on the sensorimotor system, disruption of afferent information that previously arose from mechanoreceptors responsible for proprioceptive information (*a*). These proprioceptive deficits may lead to decreased neuromuscular control (*b*), which may be observed in altered activation (magnitude) and activation patterns (timing and coordination) of 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 (*c*) of a static component of joint stability (mechanical instability) leads to functional instability (*d*). While there are instances when an individual can maintain functional joint stability after ligament injury, the majority of athletes will experience episodes of giving way and altered joint kinematics and joint kinetics. Often, individuals suffer repetitive or additional injuries to other joint structures, including other static components and dynamic components of joint stability.

A representative example of this paradigm/process is ACL injury. The primary role of the ACL is to restrain anterior translation of the tibia with respect to the femur [112]. It also has an important role in rotational stability (both IR/ER and valgus/varus) [69–71]. Injury to the ACL leads to both mechanical instability as measured by a knee arthrometer (examining movement of the tibia relative to the femur) [80] and deficits in proprioception [16, 58]. The subsequent effect of these proprioceptive deficits include altered neuromuscular control which, combined with mechanical instability, will lead to functional instability [30, 48, 128]. 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 [24]. The goals of ACL reconstruction are reestablish mechanical stability as well as restore proprioception (*c*, *a*) [54]. Rehabilitation focuses on reestablishing or improving proprioception in an attempt to improve neuromuscular control and improve functional joint stability [57, 60, 116]. Injury prevention strategies focus on proprioception, other components of function joint stability such as strength, improving neuromuscular control, improving joint kinematics during demanding tasks in order to reduce joint loading, and developing movement strategies to dissipate/decrease landing forces (*a*, *b*, *d*) with the same overall objective of improving functional joint stability [18, 39, 40, 68, 83, 93, 130]. The same emphases for injury prevention programs have also been addressed when examining the neuromuscular differences between males and females.

Noncontact Anterior Cruciate Ligament Injuries and Female Athletes

Dynamic joint stability and the prevention of knee injuries have been a core component of research at the University of Pittsburgh's Neuromuscular Research Laboratory over the last 20 years due to the demonstrated differences in noncontact ACL injury rates between male and female athletes. There exists a tremendous amount of evidence that female athletes suffer ACL injuries at a significantly higher rate than male athletes participating in the same sport [3, 6, 7, 14, 20, 26, 35–37, 77, 82, 122]. Many ACL tears occur through a noncontact mechanism where there is no external force applied directly to the lower limb or knee joint [15, 75, 86, 87]. Instead, the forces that cause the injury are applied to the knee joint via ground reaction forces and internal soft-tissue and muscle forces. Measuring gender-specific characteristics and differences is an important step in controlling and decreasing this injury (Fig. 5.2) [107]. As such, descriptive studies are used to examine predictors of injury and optimal performance. Although these types of investigations do not carry the same level of evidence as prospective studies, they do serve a purpose in assisting researchers with eliminating potential variables/characteristics that are not important or relevant to prediction and prevention of ACL injuries.

The focus in female noncontact ACL injury prevention (risk factor identification and training) continues to be on the neuromuscular and biomechanical factors of joint stability due to the potential for modification through intervention programs [18, 39, 40, 68, 83, 93, 130]. The authors' initial studies measured proprioception; electromyographic, postural stability; and strength characteristics of female athletes.[1] The gender differences observed in these factors may

[1]This chapter represents an update of a previous publication from Sell T, Lephart S: Differences in neuromuscular characteristics between male and female athletes published in Noyes' *Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes*, Saunders, Philadelphia, 2009, pp 404–414.

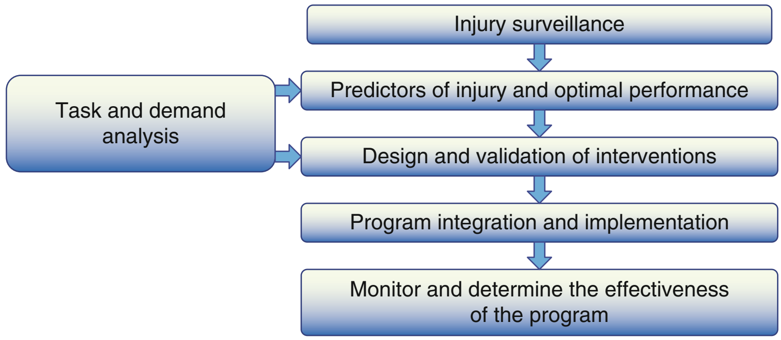


Fig. 5.2 Injury control process

result in altered neuromuscular control, a finding which has been observed in the laboratory. In addition, investigations have been conducted by the authors related to fatigue, the components of rotational (IR/ER) stability, and military populations. This chapter summarizes the authors' studies regarding gender differences in neuromuscular and biomechanical characteristics of male and female athletes and military personnel who are susceptible to noncontact ACL injury.

Proprioception

The authors define proprioception as the afferent information arising from the internal peripheral areas of the body that contributes to postural control, joint stability, and conscious sensations [59, 91]. This includes the conscious factors of proprioception: joint position sense, active and passive kinesthesia, the sense of heaviness or resistance, and appreciation of movement velocity. 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 [61]. The role of the ACL is to resist anterior translation, valgus/varus, and IR/ER rotation of the tibia on the femur [4, 11, 71]. Components of the ACL (mechanoreceptors) also provide afferent information essential to joint stability in addition to the mechanical stability that the ligament affords. Histological examination of the ligament has demonstrated the presence of several different mechanoreceptors including Ruffini endings, pacinian corpuscles, Golgi-like receptors, and free nerve endings [22, 23, 61]. 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 their increased rate of ACL injury because these deficits inhibit recruitment of the dynamic stabilizers that prevent anterior tibial translation. A study was conducted to examine the proprioceptive characteristics of male and female collegiate-level athletes [100]. Knee joint proprioception was measured by assessing threshold to detect passive motion (TTDPM) with a custom-built testing device that rotated the knee joint at 0.5°/s. The most important finding of this study was that females demonstrated diminished proprioception when the knee was rotated from 15° of knee flexion toward full extension. It was hypothesized that the decreased ability to detect motion toward a dangerous position [15, 75, 87] of full extension could interfere with the preactivation of protective muscle forces such as the hamstrings.

The authors recently conducted a study that examined the reliability, precision, and gender differences for TTDPM for IR/ER rotation of the knee [84]. The dynamometer of the Biodex System 3 Multi-Joint Testing and Rehabilitation System (Biodex Medical Inc., Shirley, NY) was adapted and modified in order to incorporate the

Fig. 5.3 Knee internal/external TTDPM setup

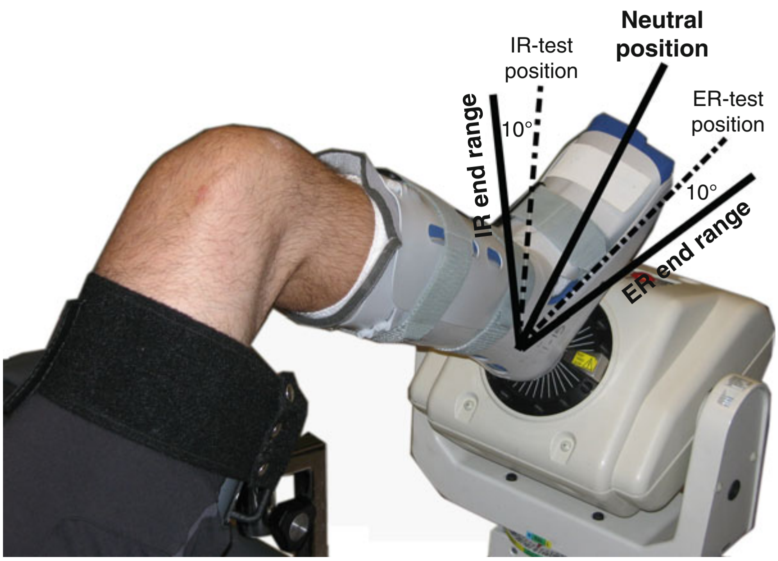


Fig. 5.4 Knee internal/external TTDPM positions

appropriate controls to eliminate visual, auditory, and tactile sensations that can confound results (Fig. 5.3). 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 internal rotation and two with the knee in a position of external rotation (Fig. 5.4). For each position, the knee was rotated toward internal rotation and external rotation. 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 internal rotation and external rotation. Similar to movement towards full extension as observed previously (see proceeding paragraph), movement towards full internal rotation loads the ACL [71].

It may be theorized that diminished proprioception negatively affects neuromuscular control and potentially places female athletes at greater risk for noncontact ACL injury. Unfortunately, limited evidence exists that demonstrates a relationship between proprioception and neuromuscular control. The authors have begun investigations to examine these relationships and recently demonstrated a significant relationship between TTDPM and joint kinematics during an athletic task [85]. The relationship between knee flexion angle at landing, knee flexion/extension TTDPM, and strength were 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 a Biodex isokinetic dynamometer, and a kinematic analysis during a single-leg stop task. Pairwise 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. A future study will examine the relationship between proprioception and other measures of functional joint stability, function (single-leg hop tests), and functional outcome measures. As part of this study, the authors are developing a measure of proprioception that may provide greater clinical insight [32] by examining active joint position sense modalities that engage the muscular protection of the knee eccentrically.

Postural Stability

Postural stability is frequently measured in athletic populations and has been shown to be a predictor of performance [106], is compromised after lower extremity musculoskeletal injuries [2, 38], is used in injury prevention training programs [55, 88, 101, 121], and has been analyzed in order to determine risk factors for lower extremity injury [1, 73, 74, 89, 99, 100, 113, 119]. 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 [110]. Postural stability is often measured in research related to knee injuries since many of the same components necessary for maintenance of postural stability are also required for dynamic joint stability. Both require establishing an equilibrium between destabilizing and stabilizing forces [72] and sensory information from vision, the vestibular system, and somatosensory feedback [49, 96].

Postural stability is typically measured under two broad testing modes, static and dynamic. Static postural stability is the ability to maintain steadiness on a fixed, firm, unmoving base of support [95]. Typically, this is measured while an individual attempts to maintain a steady state (remaining as motionless as possible) when standing on one or two legs [33]. Dynamic postural stability is the ability to transfer the vertical projection of the center of gravity around the supporting base [33]. A second definition is the ability to maintain postural stability under changing conditions, such as change in the support surface [109], following a perturbation of the individual [43, 44], or after a change in position or location such as during a single-leg jump or landing [95, 98, 124]. Dynamic postural stability has been measured with a multiple single-leg hop-stabilization test [95], a time to stabilization test [98], the star excursion test [51], and dynamic postural stability index [124]. Recently, the authors conducted a study examining the correlation between static and dynamic measures of postural stability [108]. The ultimate goal of this line of research is 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) did not correlate with two dynamic measures of postural stability: anterior-posterior jump and medial-lateral jump (measured with the dynamic postural stability index).

Gender comparisons in static postural stability measures provide additional evidence supporting the need to examine dynamic postural stability measures. The authors have compared static measures between genders in high school athletes, college athletes, and military personnel [100, 103, 107]. Females demonstrated superior static postural stability than males across all of these populations. Single-leg balance with the eyes open and closed was measured in male and female basketball players using a protocol based on that described by Goldie et al. [33, 34]. Females demonstrated significantly better single-leg balance scores for both conditions [103]. The authors' research in collegiate athletes (Division I National Collegiate Athletic Association) using the Biodex Stability System [100] found that female athletes had a significantly better stability index than their male counterparts. Over the last 5 years, the authors have conducted an injury prevention and performance optimization study with the United States Army 101st Airborne Division (Air Assault) in Ft. Campbell, KY [107]. Tactical athletes such as these soldiers suffer similar unintentional musculoskeletal injuries as civilian athletes. Static postural stability was assessed using a similar protocol to the authors' study with high school basketball players. Female soldiers demonstrated better static postural stability than male soldiers (Fig. 5.5). 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 compared to males. 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 dynamic postural stability index (DPSI) has become a common measure to examine postural stability in athletic populations. Wikstrom and colleagues have used this measure extensively, including in an examination of male and female athletes [123–127]. These authors reported that female athletes had higher DPSI scores than males in an anterior-posterior jump landing and indicated that females used different dynamic postural stability strategies than males.

The authors are currently conducting a study to examine dynamic postural stability in male

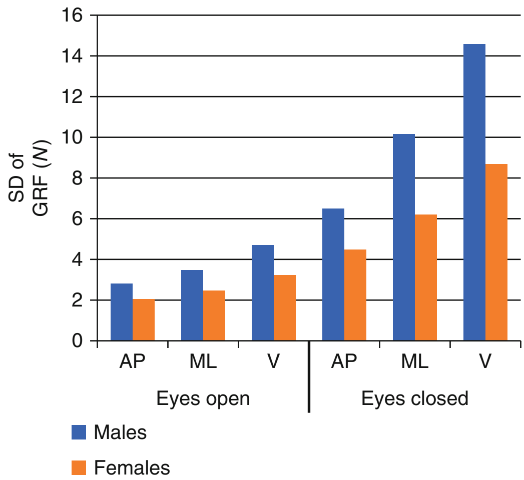


Fig. 5.5 Static postural stability in military personnel. Lower values represent better postural stability. *AP* anterior-posterior, *ML* medial-lateral, *V* vertical, *SD of GRF* standard deviation of ground reaction forces

and female lacrosse players. As part of this study, dynamic postural stability will be measured during an anterior-posterior jump landing, a medial-lateral jump landing, and a rotational jump landing (Fig. 5.6). The rotational jump landing will require the athlete to rotate 90° after initiation of the jump but before the landing phase of the task. The objective is to increase the rotational stability demand during the assessment since ACL injuries typically include a rotational component.

Electromyographic Activity

The electromyogram (EMG) represents the electrical manifestation of the contracting muscle [8] because it transmits from the neuromuscular junction along the muscle fiber [42]. Measurement of EMG activity produces information regarding the amount of electrical activity in the contracting muscle, which in turn provides insight into the magnitude of tension developed [129]. Relative to the functional joint stability paradigm (Fig. 5.1), EMG can describe neuromuscular control as well as the attempt to maintain functional joint stability (or inability to maintain functional joint stability). Unfortunately, many

Fig. 5.6 Rotational dynamic postural stability index

factors may influence this signal, therefore creating difficulty in interpreting 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, required to reduce strain in the ACL, is directly related to the neuromuscular control of the knee musculature. In order for this control to be effective, the central nervous system (CNS) must be able to anticipate destabilizing forces and act appropriately [12]. The EMG activity of the upper arm musculature during reaction time arm movements was measured by Benvenuti et al. [10]. These investigators reported 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. 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 [13, 19, 67].

The authors have examined EMG activity of the knee in order to determine differences between genders in dynamic stabilization strategies [100], to examine the demands of different athletic tasks [104], to determine differences between planned and reactive tasks [104], and to determine predictors of proximal anterior tibia shear force [105]. In a study involving collegiate-level soccer players, Rozzi and colleagues [100] demonstrated that females activated the lateral hamstrings differently than males during a drop-landing task. Females had a greater peak amplitude and integrated EMG (IEMG) for lateral hamstrings in response to the landing. The authors concluded that this finding represented an attempt by female athletes to prevent the anterior tibial translation that occurs during this task. Similar observations were made in high school male and female basketball players while they performed planned and reactive stop-jump tasks [104]. Reactive tasks were included in this study in order to better simulate actual athletic competitions when athletes have to react quickly to other competitors. The female players demonstrated greater IEMG activity of the semitendinosus and a higher cocontraction value during the 150 ms prior to the initial landing compared to the male players for planned and reactive tasks. These gender differences observed in semitendinosus activity during these stop-jump tasks are consistent with a previous study [100] and reinforce the concept that females use compensatory strategies to counter the decreased knee joint proprioception in order to achieve functional joint stabilization.

The data obtained from studies that analyzed EMG activation patterns, timing, amplitude, and quantity have increased our understanding of the mechanisms of male and female athletes that occur in order to achieve functional joint stability in the presence of destabilizing forces and moments. Currently, the authors are developing a dynamic, muscle-driven musculoskeletal model that integrates anatomical and physiological components with experimental data to derive neuromuscular excitation patterns that generate appropriate muscle forces and joint kinematics/kinetics. This forward dynamics approach will allow the use of EMG data to derive models of functional joint stability based on joint kinematic and joint kinetic data.

Strength

The dynamic components of joint stability are dependent on the characteristics of the underlying muscles, including strength [96]. 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 may reduce the amount of strain, whereas the quadriceps may increase the amount of strain [28, 94]. 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.

The authors' research has consistently demonstrated that males have significantly greater strength than females. Male collegiate (Division I National Collegiate Athletic Association) volleyball, basketball, and soccer athletes have significantly stronger knee extension and flexion strength compared to females of similar age and activity level [63]. Similar differences between genders in isokinetic knee strength have been observed between male and female high school basketball players [103]. Strength comparisons between male and female soldiers of the US 101st Airborne (Air Assault) Division have also been performed [107]. Similar to civilian athletes, male soldiers demonstrated significantly greater isokinetic knee extensor and flexor strength than female soldiers (Fig. 5.7).

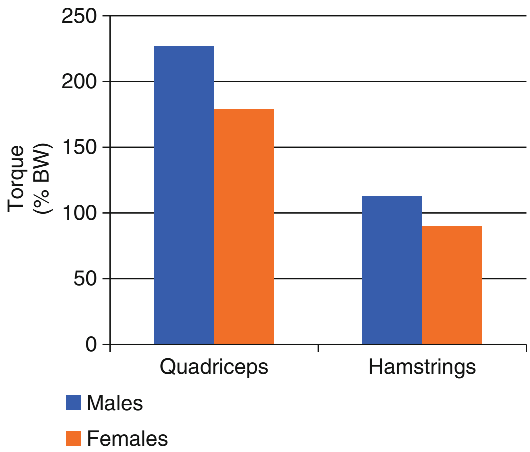


Fig. 5.7 Hamstrings and quadriceps strength in military personnel. *BW* body weight

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 [81] prospectively demonstrated that females who suffered ACL injury had a lower H:Q strength ratio compared to female controls and male controls who did not suffer ACL injury. These authors also demonstrated that females who subsequently suffered an ACL injury had lower hamstrings strength, but not lower quadriceps strength, compared to males who did not suffer an ACL injury. The authors' studies have consistently demonstrated that females and males have similar H:Q strength ratios when using similar isokinetic speeds (Fig. 5.8). It is important to

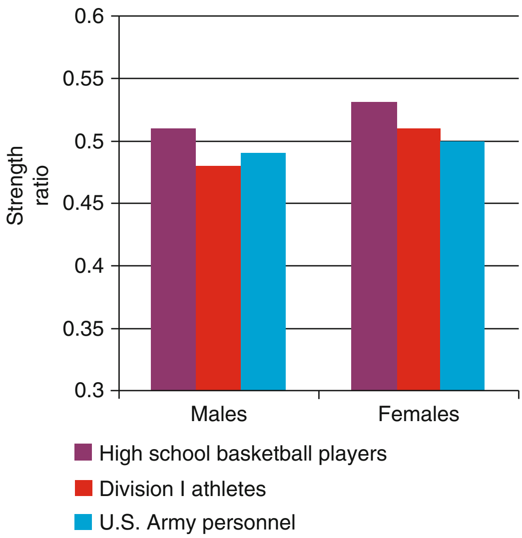


Fig. 5.8 Hamstrings-to-quadriceps strength ratios across athletes and military personnel

note that these studies represent comparisons between uninjured groups.

Recently, the authors examined isometric internal/external tibia rotation strength in male and female athletes, as well as the relationship between knee flexion/extension strength and landing kinematics [85]. Internal and external isometric strength was measured with the Biodex System 3 Multi-Joint Testing and Rehabilitation System with a similar setup as described with TTDPM testing. Female athletes demonstrated lower internal rotation and lower external rotation strength compared to male athletes (Fig. 5.9). These results are consistent with other gender comparisons in knee strength. Nagai and colleagues [85] also reported a significant relationship between knee extension strength and knee flexion angle on landing; as quadriceps strength increased, so did knee flexion angle at initial contact. In terms of ACL injury, landing in a more flexed position is believed to be safer than landing in an extended position [27, 71, 102]. 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.

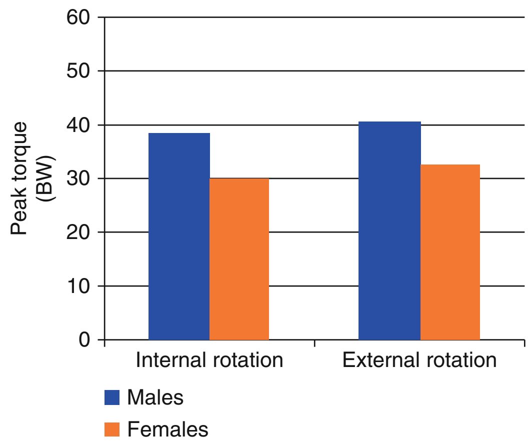


Fig. 5.9 Knee internal/external rotation strength. *BW* body weight

Biomechanics

The functional joint stability paradigm (Fig. 5.1) 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. The authors have examined the biomechanics of males and females during several different tasks in order to determine how neuromuscular control (deficits) affects landing kinematics and kinetics.

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 [63, 104]. As previously mentioned, the authors are currently examining risk factors for injury in male and female soldiers who have undergone a biomechanical assessment during a stop-jump task and a vertical drop landing. A preliminary analysis of these data demonstrate that female soldiers land with greater valgus at initial contact compared to male soldiers.

Biomechanical analyses of tasks implicated in knee injuries are a continued focus of the authors' laboratories. Research has been expanded to incorporate emerging technology, including the use of wireless three-dimensional accelerometers that have the potential to be used during actual competition. Current work involves studying the relationships among knee joint forces as measured through inverse dynamics, tibial accelerations as measured with a wireless three-dimensional accelerometer, and tibial translation as measured with a dynamic stereo x-ray system. The ultimate goal of this research is to develop robust but portable instrumentation to collect relevant biomechanical data away from traditional laboratory environments.

Fatigue

Epidemiological studies of fatigue and risk of injury have demonstrated across multiple sports that more injuries occur during the later stages of activity and competition [25, 29, 79, 90, 97, 115]. These observations include muscular injuries, joint injuries, and noncontact ACL injuries [66]. Rozzi and associates observed that muscular fatigue can disrupt or degrade the compensatory stabilizing mechanisms necessary to maintain joint stability in the presence of destabilizing forces and moments [99]. Although the factors that cause this disruption of normal stabilizing mechanisms are unclear, they may include an increase in knee joint laxity [45, 99, 111] or a reduction in neuromuscular control [47, 131], balance skill [47], or proprioception [41, 52, 53, 78]. Multiple studies from the authors' laboratory have examined the effects of fatigue on neuromuscular and biomechanical characteristics of female and male athletes.

The authors measured knee joint laxity, kinesthesia (via TTDPM), lower extremity balance, and surface EMG activity during a landing maneuver in male and female athletes before and after a peripheral muscular fatigue protocol [99] that induced fatigue of the knee flexors and extensors. The protocol was performed with the 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 integrated EMG of the vastus lateralis and vastus medialis after landing. Both males and females were affected equally. The authors have also demonstrated that fatigue, induced by an exhaustive run [50, 92], forces adaptations in landing kinematics equally in both genders [9]. Both male and female recreational athletes demonstrated a decreased knee flexion angle at initial contact and decreased maximum valgus angle, which were theorized to be an attempt to gain knee stability. Overall, it appears as though fatigue affects both genders equally and places both male and female athletes at greater risk for injury.

Currently, the authors are examining physiological variables such as anaerobic capacity, aerobic capacity, and muscular endurance to determine if they can reduce the effects of fatigue on neuromuscular and biomechanical risk factors for injury. During a pilot study, fatigue was induced with a maximum oxygen uptake treadmill test and during a test of anaerobic power and capacity. Both protocols significantly affected postural stability during a single-leg balance task, with the effects of fatigue persisting for 8 min. In an upcoming study, the determination will be made if greater physical fitness (muscular strength, aerobic capacity, and anaerobic capacity) delays the effects of a simulated athletic competition on proprioception. It is anticipated that the results of this study will help determine appropriate training strategies to reduce fatigue and risk of injury.

Current Research

The authors continue to conduct research on injury prevention and control in female athletes and army soldiers. Research has expanded to include performance optimization research with several other groups across different branches of the military. Human performance testing has been incorporated in order to improve specificity of training relative to the physiological, musculoskeletal, and neuromuscular demands of tactical training and mission execution. The ultimate goals of these projects are to reduce the incidence and severity of injuries, minimize the necessity for surgery, promote longevity, enhance performance, optimize military readiness, and improve the overall health of military personnel during service and after they leave the military. The authors are also developing and validating the capability of portable instrumentation that can be used in place of more expensive equipment typically used in laboratory settings.

References

1. Abt JP, Sell TC, Laudner KG et al (2007) Neuromuscular and biomechanical characteristics do not vary across the menstrual cycle. Knee Surg Sports Traumatol Arthrosc 15(7):901–907
2. Ageberg E, Roberts D, Holmstrom E et al (2005) Balance in single-limb stance in patients with anterior cruciate ligament injury: relation to knee laxity, proprioception, muscle strength, and subjective function. Am J Sports Med 33(10):1527–1535
3. Agel J, Arendt EA, Bershadsky B (2005) Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. Am J Sports Med 33(4):524–530
4. Ahmed AM, Hyder A, Burke DL et al (1987) In-vitro ligament tension pattern in the flexed knee in passive loading. J Orthop Res 5(2):217–230
5. Andriacchi TP, Briant PL, Bevill SL et al (2006) Rotational changes at the knee after ACL injury cause cartilage thinning. Clin Orthop Relat Res 442:39–44
6. Arendt E, Dick R (1995) Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. Am J Sports Med 23(6):694–701
7. Arendt EA, Agel J, Dick R (1999) Anterior cruciate ligament injury patterns among collegiate men and women. J Athl Train 34(2):86–92
8. Basmajian JV (1978) Muscles alive, their functions revealed by electromyography, 4th edn. Williams & Wilkins, Baltimore
9. Benjaminse A, Habu A, Sell TC et al (2008) Fatigue alters lower extremity kinematics during a single-leg stop-jump task. Knee Surg Sports Traumatol Arthrosc 16(4):400–407
10. Benvenuti F, Stanhope SJ, Thomas SL et al (1997) Flexibility of anticipatory postural adjustments revealed by self-paced and reaction-time arm movements. Brain Res 761(1):59–70
11. Berns GS, Hull ML, Patterson HA (1992) Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. J Orthop Res 10(2):167–176
12. Besier TF, Lloyd DG, Ackland TR et al (2001) Anticipatory effects on knee joint loading during running and cutting maneuvers. Med Sci Sports Exerc 33(7):1176–1181
13. Besier TF, Lloyd DG, Ackland TR (2003) Muscle activation strategies at the knee during running and cutting maneuvers. Med Sci Sports Exerc 35(1):119–127
14. Bjordal JM, Arnoy F, Hannestrad B et al (1997) Epidemiology of anterior cruciate ligament injuries in soccer. Am J Sports Med 25(3):341–345
15. Boden BP, Dean GS, Feagin JA Jr et al (2000) Mechanisms of anterior cruciate ligament injury. Orthopedics 23(6):573–578
16. Borsa PA, Lephart SM, Irrgang JJ et al (1997) The effects of joint position and direction of joint motion on proprioceptive sensibility in anterior cruciate ligament-deficient athletes. Am J Sports Med 25(3):336–340
17. Butler DL, Noyes FR, Grood ES (1980) Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. J Bone Joint Surg Am 62(2):259–270
18. Caraffa A, Cerulli G, Projetti M et al (1996) Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. Knee Surg Sports Traumatol Arthrosc 4(1):19–21
19. Cowling EJ, Steele JR (2001) Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates. J Electromyogr Kinesiol 11(4):263–268
20. Cox JS, Lenz HW (1984) Women midshipmen in sports. Am J Sports Med 12(3):241–243
21. Daniel DM, Malcolm LL, Losse G et al (1985) Instrumented measurement of anterior laxity of the knee. J Bone Joint Surg Am 67A:720–726
22. Denti M, Monteleone M, Berardi A et al. (1994) Anterior cruciate ligament mechanoreceptors. Histologic studies on lesions and reconstruction. Clin Orthop Relat Res 308:29–32
23. Duthon VB, Barea C, Abrassart S et al (2006) Anatomy of the anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 14(3):204–213
24. Eastlack ME, Axe MJ, Snyder-Mackler L (1999) Laxity, instability, and functional outcome after ACL injury: copers versus noncopers. Med Sci Sports Exerc 31(2):210–215
25. Feagin JA Jr, Lambert KL, Cunningham RR et al (1987) Consideration of the anterior cruciate ligament injury in skiing. Clin Orthop Relat Res 216:13–18
26. Ferretti A, Papandrea P, Conteduca F et al (1992) Knee ligament injuries in volleyball players. Am J Sports Med 20(2):203–207
27. Fleming BC, Renstrom PA, Beynnon BD et al (2001) The effect of weightbearing and external loading on anterior cruciate ligament strain. J Biomech 34(2):163–170
28. Fleming BC, Ohlen G, Renstrom PA et al (2003) The effects of compressive load and knee joint torque on

peak anterior cruciate ligament strains. Am J Sports Med 31(5):701–707
29. Gabbett TJ (2000) Incidence, site, and nature of injuries in amateur rugby league over three consecutive seasons. Br J Sports Med 34(2):98–103
30. Gardinier ES, Manal K, Buchanan TS et al (2012) Gait and neuromuscular asymmetries after acute ACL rupture. Med Sci Sports Exerc 44(8):1490–1496
31. Ghez C, Krakauer J (2000) The organization of movement. In: Kandel ER, Schwartz JH, Jessell TM (eds) Principles of neural science. McGraw-Hill,Health Professions Division, New York, pp 653–673
32. Gokeler A, Benjaminse A, Hewett TE et al (2012) Proprioceptive deficits after ACL injury: are they clinically relevant? Br J Sports Med 46(3):180–192
33. Goldie PA, Bach TM, Evans OM (1989) Force platform measures for evaluating postural control: reliability and validity. Arch Phys Med Rehabil 70(7):510–517
34. Goldie PA, Evans OM, Bach TM (1992) Steadiness in one-legged stance: development of a reliable force-platform testing procedure. Arch Phys Med Rehabil 73(4):348–354
35. Gomez E, DeLee JC, Farney WC (1996) Incidence of injury in Texas girls' high school basketball. Am J Sports Med 24(5):684–687
36. Gwinn DE, Wilckens JH, McDevitt ER et al (2000) The relative incidence of anterior cruciate ligament injury in men and women at the United States Naval Academy. Am J Sports Med 28(1):98–102
37. Harrer MR, Berson L, Hosea TM et al. (1996) Lower extremity injuries: females vs. males in the sport of basketball. Paper presented at the AOSSM 22nd Annual Meeting, Lake Buena Vista, FL
38. Herrington L, Hatcher J, Hatcher A et al (2009) A comparison of star excursion balance test reach distances between ACL deficient patients and asymptomatic controls. Knee 16(2):149–152
39. Hewett TE, Stroupe AL, Nance TA et al (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24(6):765–773
40. Hewett TE, Lindenfeld TN, Riccobene JV et al (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27(6):699–706
41. Hiemstra LA, Lo IK, Fowler PJ (2001) Effect of fatigue on knee proprioception: implications for dynamic stabilization. J Orthop Sports Phys Ther 31(10):598–605
42. Hillstrom HJ, Triolo RJ (1995) EMG theory. In: Craik RL, Oatis CA (eds) Gait analysis: theory and appplication, 1st edn. Mosby, St. Louis
43. Hoffman M, Schrader J, Koceja D (1999) An investigation of postural control in postoperative anterior cruciate ligament reconstruction patients. J Athl Train 34(2):130–136
44. Hoffman MA, Koceja DM (1997) Dynamic balance testing with electrically evoked perturbation: a test of reliability. Arch Phys Med Rehabil 78(3):290–293
45. Huston LJ, Wojtys EM (1996) Neuromuscular performance characteristics in elite female athletes. Am J Sports Med 24(4):427–436
46. Johansson H, Sjolander P (1993) Neurophysiology of joints. In: Wright V, Radin EL (eds) Mechanics of human joints. Physiology, pathophysiology, and treatment. Marcel Dekker, Inc, New York, pp 243–290
47. Johnston RB 3rd, Howard ME, Cawley PW et al (1998) Effect of lower extremity muscular fatigue on motor control performance. Med Sci Sports Exerc 30(12):1703–1707
48. Kalund S, Sinkjer T, Arendt-Nielsen L et al (1990) Altered timing of hamstring muscle action in anterior cruciate ligament deficient patients. Am J Sports Med 18(3):245–248
49. Kandel ER, Schwartz JH, Jessell TM (1991) Principles of neural science. Appleton & Lange, Norwalk
50. Kang J, Chaloupka EC, Mastrangelo MA et al (2001) Physiological comparisons among three maximal treadmill exercise protocols in trained and untrained individuals. Eur J Appl Physiol 84(4):291–295
51. Kinzey SJ, Armstrong CW (1998) The reliability of the star-excursion test in assessing dynamic balance. J Orthop Sports Phys Ther 27(5):356–360
52. Lattanzio PJ, Petrella RJ, Sproule JR et al (1997) Effects of fatigue on knee proprioception. Clin J Sport Med 7(1):22–27
53. Lattanzio PJ, Petrella RJ (1998) Knee proprioception: a review of mechanisms, measurements, and implications of muscular fatigue. Orthopedics 21(4):463–470; discussion 470–461; passim
54. Lephart S, Kocher MS, Fu F et al (1992) Proprioception following anterior cruciate ligament reconstruction. J Sport Rehab 1:188–196
55. Lephart S, Myers JB, Sell TC et al (2007) Golf injury prevention: an orthopedic approach through physical testing, biomechanics, and training. Paper presented at the AAOS Annual Meeting, San Diego, CA
56. Lephart SM, Warner JP, Borsa PA et al (1994) Proprioception of the shoulder joint in healthy, unstable, and surgically repaired shoulders. J Shoulder Elbow Surg 3(6):371–380
57. Lephart SM, Henry TJ (1995) Functional rehabilitation for the upper and lower extremity. Orthop Clin North Am 26:579–592
58. Lephart SM, Pincivero DM, Giraldo JL et al (1997) The role of proprioception in the management and rehabilitation of athletic injuries. Am J Sports Med 25(1):130–137
59. Lephart SM, Pincivero DM, Rozzi SL (1998) Proprioception of the ankle and knee. Sports Med 25(3):149–155
60. Lephart SM, Fu FH (2000) Proprioception and neuromuscular control in joint stability. Human Kinetics, Champaign
61. Lephart SM, Riemann BL, Fu FH (2000) Proprioception and neuromuscular control in joint stability. In: Lephart SM, Fu FH (eds) Introduction to the sensorimotor system. Human Kinetics, Champaign, pp xvii–xxiv

62. Lephart SM, Abt JP, Ferris CM (2002) Neuromuscular contributions to anterior cruciate ligament injuries in females. Curr Opin Rheumatol 14(2):168–173
63. Lephart SM, Ferris CM, Riemann BL et al (2002) Gender differences in strength and lower extremity kinematics during landing. Clin Orthop 401:162–169
64. LeVeau BR, Williams M (1992) Williams & Lissner's biomechanics of human motion, 3rd edn. W.B. Saunders Co., Philadelphia
65. Lew WD, Lewis JL, Craig EV (1993) Stabilization by capsule, ligaments, and labrum: stability at the extremes of motion. In: Matsen FA, Fu FH, Hawkins RJ (eds) The shoulder: a balance of mobility and stability. American Academy of Orthopaedic Surgeons, Rosemont, pp 69–89
66. Liederbach M, Dilgen FE, Rose DJ (2008) Incidence of anterior cruciate ligament injuries among elite ballet and modern dancers: a 5-year prospective study. Am J Sports Med 36(9):1779–1788
67. Malinzak RA, Colby SM, Kirkendall DT (2001) A comparison of knee joint motion patterns between men and women in selected athletic tasks. Clin Biomech (Bristol, Avon) 16(5):438–445
68. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010
69. Markolf KL, Mensch JS, Amstutz HC (1976) Stiffness and laxity of the knee–the contributions of the supporting structures. A quantitative in vitro study. J Bone Joint Surg Am 58(5):583–594
70. Markolf KL, Gorek JF, Kabo JM et al (1990) Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. J Bone Joint Surg Am 72(4):557–567
71. Markolf KL, Burchfield DM, Shapiro MM et al (1995) Combined knee loading states that generate high anterior cruciate ligament forces. J Orthop Res 13(6):930–935
72. McCollum G, Leen TK (1989) Form and exploration of mechanical stability limits in erect stance. J Mot Behav 21(3):225–244
73. McGuine TA, Keene JS (2006) The effect of a balance training program on the risk of ankle sprains in high school athletes. Am J Sports Med 34(7):1103–1111
74. McHugh MP, Tyler TF, Tetro DT et al (2006) Risk factors for noncontact ankle sprains in high school athletes: the role of hip strength and balance ability. Am J Sports Med 34(3):464–470
75. McNair PJ, Marshall RN, Matheson JA (1990) Important features associated with acute anterior cruciate ligament injury. N Z Med J 103(901):537–539
76. McNair PJ, Marshall RN (1994) Landing characteristics in subjects with normal and anterior cruciate ligament deficient knee joints. Arch Phys Med Rehabil 75(5):584–589
77. Messina DF, Farney WC, DeLee JC (1999) The incidence of injury in Texas high school basketball. A prospective study among male and female athletes. Am J Sports Med 27(3):294–299
78. Miura K, Ishibashi Y, Tsuda E et al (2004) The effect of local and general fatigue on knee proprioception. Arthroscopy 20(4):414–418
79. Molsa J, Airaksinen O, Nasman O et al (1997) Ice hockey injuries in Finland. A prospective epidemiologic study. Am J Sports Med 25(4):495–499
80. Musahl V, Seil R, Zaffagnini S et al (2012) The role of static and dynamic rotatory laxity testing in evaluating ACL injury. Knee Surg Sports Traumatol Arthrosc 20(4):603–612
81. Myer GD, Ford KR, Barber Foss KD et al (2009) The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. Clin J Sport Med 19(1):3–8
82. Myklebust G, Maehlum S, Holm I et al (1998) A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. Scand J Med Sci Sports 8(3):149–153
83. Myklebust G, Engebretsen L, Braekken IH et al (2003) Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. Clin J Sport Med 13(2):71–78
84. Nagai T, Sell TC, Abt JP et al. (2012) Reliability, precision, and gender differences in knee internal/external rotation proprioception measurements. Phys Ther Sport (In Press)
85. Nagai T, Sell TC, House AJ et al. (2012) Knee proprioception and strength are correlated with landing kinematics during a single-leg stop-jump task. J Athl Train
86. Noyes FR, Matthews DS, Mooar PA (1983) The symptomatic anterior cruciate-deficient knee. Part II: the results of rehabilitation, activity modification, and counseling on functional disability. J Bone Joint Surg Am 65(2):163–174
87. Olsen OE, Myklebust G, Engebretsen L et al (2004) Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am J Sports Med 32(4):1002–1012
88. Paterno MV, Myer GD, Ford KR et al (2004) Neuromuscular training improves single-limb stability in young female athletes. J Orthop Sports Phys Ther 34(6):305–316
89. Paterno MV, Schmitt LC, Ford KR et al (2010) Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. Am J Sports Med 38(10):1968–1978
90. Pettrone FA, Ricciardelli E (1987) Gymnastic injuries: the Virginia experience 1982–1983. Am J Sports Med 15(1):59–62
91. Pincivero DM, Lephart SM, Karunakara RA (1997) Reliability and precision of isokinetic strength and muscular endurance for the quadriceps and hamstrings. Int J Sports Med 18(2):113–117
92. Pollock LM, Wilmore JH, Fox SM (1978) Health and fitness through physical activity. Wiley, New York

93. Prapavessis H, McNair PJ (1999) Effects of instruction in jumping technique and experience jumping on ground reaction forces. J Orthop Sports Phys Ther 29(6):352–356
94. Renstrom P, Arms SW, Stanwyck TS et al (1986) Strain within the anterior cruciate ligament during hamstring and quadriceps activity. Am J Sports Med 14(1):83–87
95. Riemann BL, Caggiano NA, Lephart SM (1999) Examination of a clinical method of assessing postural control during a functional performance test. J Sport Rehabil 8:171–183
96. Riemann BL, Lephart SM (2002) The sensorimotor system, part I: the physiologic basis of functional joint stability. J Athl Train 37(1):71–79
97. Rodacki AL, Fowler NE, Bennett SJ (2002) Vertical jump coordination: fatigue effects. Med Sci Sports Exerc 34(1):105–116
98. Ross S, Guskiewicz KM (2003) Time to stabilization: a method for analyzing dynamic postural stability. Int J Athl Ther Train 8(3):37–39
99. Rozzi SL, Lephart SM, Fu FH (1999) Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. J Athl Train 34(2):106–114
100. Rozzi SL, Lephart SM, Gear WS et al (1999) Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. Am J Sports Med 27(3):312–319
101. Rozzi SL, Lephart SM, Sterner R et al (1999) Balance training for persons with functionally unstable ankles. J Orthop Sports Phys Ther 29(8): 478–486
102. Sakane M, Fox RJ, Woo SL et al (1997) In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. J Orthop Res 15(2): 285–293
103. Sell TC, Myers JB, Youk AO et al. (2004) Neuromechanical predictors of dynamic stability. University of Pittsburgh, University of Pittsburgh website
104. Sell TC, Ferris CM, Abt JP et al (2006) The effect of direction and reaction on the neuromuscular and biomechanical characteristics of the knee during tasks that simulate the noncontact anterior cruciate ligament injury mechanism. Am J Sports Med 34(1): 43–54
105. Sell TC, Ferris CM, Abt JP et al (2007) Predictors of proximal tibia anterior shear force during a vertical stop-jump. J Orthop Res 25(12):1589–1597
106. Sell TC, Tsai YS, Smoliga JM et al (2007) Strength, flexibility, and balance characteristics of highly proficient golfers. J Strength Cond Res 21(4): 1166–1171
107. Sell TC, Abt JP, Crawford K et al (2010) Warrior model for human performance and injury prevention: eagle tactical athlete program (ETAP) part I. J Spec Oper Med 10(4):2–21
108. Sell TC, Huang HC, Abt JP et al (2012) An examination, correlation, and comparison of static and dynamic measures of postural stability in healthy, physically active adults. Phys Ther Sport 13(2): 80–86
109. Shultz SJ, Perrin DH, Adams JM et al (2000) Assessment of neuromuscular response characteristics at the knee following a functional perturbation. J Electromyogr Kinesiol 10(3):159–170
110. Shumway-Cook A, Woollacott MH (2001) Motor control: theory and practical applications, 2nd edn. Lippincott, Williams & Wilkins, Philadelphia
111. Skinner HB, Wyatt MP, Hodgdon JA et al (1986) Effect of fatigue on joint position sense of the knee. J Orthop Res 4(1):112–118
112. Smith BA, Livesay GA, Woo SL (1993) Biology and biomechanics of the anterior cruciate ligament. Clin Sports Med 12(4):637–670
113. Soderman K, Alfredson H, Pietila T et al (2001) Risk factors for leg injuries in female soccer players: a prospective investigation during one out-door season. Knee Surg Sports Traumatol Arthrosc 9:313–321
114. Solomonow M, Krogsgaard M (2001) Sensorimotor control of knee stability. A review. Scand J Med Sci Sports 11(2):64–80
115. Stuart MJ, Smith A (1995) Injuries in junior A ice hockey. A three-year prospective study. Am J Sports Med 23(4):458–461
116. Swanik CB, Lephart SM, Giannantonio FP et al (1997) Reestablishing proprioception and neuromuscular control in the ACL-injured athlete. J Sport Rehabil 6:182–206
117. Tashman S, Collon D, Anderson K et al (2004) Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am J Sports Med 32(4):975–983
118. Tashman S, Kolowich P, Collon D et al (2007) Dynamic function of the ACL-reconstructed knee during running. Clin Orthop Relat Res 454:66–73
119. Tyler TF, McHugh MP, Mirabella MR et al (2006) Risk factors for noncontact ankle sprains in high school football players: the role of previous ankle sprains and body mass index. Am J Sports Med 34(3):471–475
120. Venes D, Thomas CL, Taber CW (2001) Taber's cyclopedic medical dictionary, 19th edn. F.A. Davis Co, Philadelphia, llustrated in full color
121. Verhagen E, van der Beek A, Twisk J et al (2004) The effect of a proprioceptive balance board training program for the prevention of ankle sprains: a prospective controlled trial. Am J Sports Med 32(6): 1385–1393
122. Walden M, Hagglund M, Werner J et al (2011) The epidemiology of anterior cruciate ligament injury in football (soccer): a review of the literature from a gender-related perspective. Knee Surg Sports Traumatol Arthrosc 19(1):3–10
123. Wikstrom EA, Tillman MD, Borsa PA (2005) Detection of dynamic stability deficits in subjects with functional ankle instability. Med Sci Sports Exerc 37(2):169–175

124. Wikstrom EA, Tillman MD, Smith AN et al (2005) A new force-plate technology measure of dynamic postural stability: the dynamic postural stability index. J Athl Train 40(4):305–309
125. Wikstrom EA, Tillman MD, Chmielewski TL et al (2006) Measurement and evaluation of dynamic joint stability of the knee and ankle after injury. Sports Med 36(5):393–410
126. Wikstrom EA, Tillman MD, Kline KJ et al (2006) Gender and limb differences in dynamic postural stability during landing. Clin J Sport Med 16(4):311–315
127. Wikstrom EA, Tillman MD, Chmielewski TL et al (2007) Dynamic postural stability deficits in subjects with self-reported ankle instability. Med Sci Sports Exerc 39(3):397–402
128. Williams GN, Barrance PJ, Snyder-Mackler L et al (2004) Altered quadriceps control in people with anterior cruciate ligament deficiency. Med Sci Sports Exerc 36(7):1089–1097
129. Winter DA (1990) Biomechanics and motor control of human movement, 2nd edn. Wiley, New York
130. Wojtys EM, Huston LJ, Taylor PD et al (1996) Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. Am J Sports Med 24(2):187–192
131. Wojtys EM, Wylie BB, Huston LJ (1996) The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. Am J Sports Med 24(5):615–621

Gender Differences in Muscular Protection of the Knee

6

Benjamin Noonan and Edward M. Wojtys

Contents

B. Noonan, M.D. (✉)
MedSport Orthopaedics, University of Michigan,
24 Frank Lloyd Wright Drive, Ann Arbor,
MI 48106-0391, USA
e-mail: noonanb@med.umich.edu

E.M. Wojtys, M.D.
MedSport Orthopaedics, University of Michigan,
24 Frank Lloyd Wright Drive, Ann Arbor,
MI 48106-0391, USA

Department of Orthoapedic Surgery,
University of Michigan,
Ann Arbor, MI, USA

Sports Medicine Service, University of Michigan,
Ann Arbor, MI, USA
e-mail: edwojtys@umich.edu

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" [22], 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 modes, including eccentric, isotonic, and isometric 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

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_6, © Springer-Verlag Berlin Heidelberg 2012

balance. Input processing is frequently determined by measuring muscular reaction times and muscular responses according to the time to generate peak torque during voluntary muscular contractions of the knee.

Qualities of the Knee

Laxity

Laxity has been defined as "indicating slackness or lack of tension in a ligament" [22], 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. Although ligamentous laxity is often proposed as a risk factor for knee injury, the evidence is not overwhelming [21, 39]. 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 [39]. In this cohort, generalized laxity and KT-2000 anterior tibial translation were significantly greater in individuals who sustained a noncontact ACL injury than 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 [21]. Given the relationship of laxity and ACL injury risk, others have sought to determine if laxity is modifiable or affected by other variables.

Fatigue is commonly experienced during athletic events which have led some investigators to investigate its effects on laxity. Studies conducted on collegiate soccer and basketball players found that females had significantly greater AP translation at rest than males (6.05 and 4.80 mm; respectively, $P=0.021$), which did not change significantly after a fatiguing protocol [30, 31]. 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 was recorded, resulted in an increase in AP translation without significant differences between men and women [42].

Another variable which may affect laxity is hormonal fluctuations that occur over the course of a menstrual cycle [26, 28, 35, 36, 45]. The effects of hormonal levels on laxity are variable; a systematic review reported mixed results with six of nine studies reporting no differences [45]. Newer evidence points to increased AP laxity [26], genu recurvatum, and generalized joint laxity [36] across the menstrual cycle.

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 is not clear; newer data show increased translation across the menstrual cycle.
- The impact of fatigue on AP tibial translation is mixed.

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 [38, 42]. 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 [43]. The ability to increase muscle stiffness across a joint can reduce damaging loads that have the potential to injure ligaments and other passive structures [4, 11, 12, 43, 44]. In general, males produce greater active stiffness than females [11, 12, 43, 44].

Men have been shown to be able to actively increase their muscle stiffness in response to an anterior tibial translation threefold compared to a twofold increase generated by women (Table 6.1) [43]. 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 to females [4, 12].

Several of these aforementioned studies have been conducted in laboratory settings to measure knee joint stiffness, while others have used a more functional protocol [11]. For instance, Granata et al. [11] reported that in 2-legged hopping tasks (2.5 Hz, 3.0 Hz, or at a preferred hopping rate), male subjects maintained greater stiffness at all frequencies compared to females (Table 6.1).

Stiffness may be measured in both the AP dimension or as a rotational component. The dynamic rotational stiffness of 24 Division I 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° [44]. 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 [44]. The decreased rotational stiffness in females is of concern because it has been shown that internal rotation tibial torque is a potent stressor of the ACL [25].

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.

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 [40]. 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 contact [40]. 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 [16]. 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 [39]. Evidence suggests that knee flexors have the potential to reduce stress on the ACL. The knee extensors function more as an antagonist [41], but

Table 6.1 Gender differences in muscular stiffness

Study	Subject data	Testing protocol, ° knee flexion	Results			
			Male	Female	Difference (%)	Difference significant?
Blackburn et al. [4]	18–28 yo recreational athletes	30° flexion	Nm/rad:			
			223.7 ± 40.2	160.7 ± 23.2	48	Yes
Granata et al. [11]	21–33 yo recreational athletes	Hopping rate:	kN/m:			
		2.5 Hz	31 ± 8	24 ± 5	29	Yes
		3.0 Hz	43 ± 8	35 ± 7	23	Yes
		Preferred	26 ± 9	19 ± 8	37	Yes
Granata et al. [12]	21–33 yo recreational athletes		Nm/rad:			
		Quadriceps 0 kg perturbation	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. [43]	19–31 yo sedentary to elite athletes	Sagittal shear stiffness	N/mm:			
			70.9	40.7	74	Yes
Wojtys et al. [44]	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

Data shown are mean ± standard deviation
MVE maximal voluntary exertions, *yo* year-old
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

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 [1, 2, 6, 7, 13, 29].

Not surprisingly, athletes demonstrate greater absolute quadriceps and hamstring strength compared to gender matched nonathletic controls [6]. Male athletes consistently display increased normalized quadriceps strength (29–38 %) compared to female athletes, while mixed results are reported for hamstring strength (Table 6.2) [20, 27, 43]. Higher H:Q ratios have been measured in some male high school athletes [1, 13], while others [6, 29] failed to replicate these results (Table 6.3).

Peak knee extensor and flexor torque increases with maturation in both sexes [3]. 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 [17]. When comparing H:Q ratios, immature (10–13-year-old) female soccer players demonstrate reduced ratios compared to males and mature (14–18-year-old) females in some, but not all studies [3, 7, 17].

Another area of discussion 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 [24], 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 to 360°/s (Fig. 6.1), whereas females are not able to do so [15]. This finding is consistent with other maturation-specific gender differences in neuromuscular control, but no definitive mechanism has been proposed [14]. 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 [1, 6, 29].

Similar to laxity, strength may be 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 [9, 32, 37]. Protocols that induce fatigue include sprints [9, 37] and isokinetic knee extension and flexion [32]. 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 and show mixed results, some studies report greater ratios in male versus female athletes.
- 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.

Neuromuscular System

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. Balance performance appears to be trainable and may lead to improvement in athletic performance [47].

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 to males (2.95° and 2.11°, respectively, $P = 0.04$) [31]. There were no significant gender differences in TTDPM when the knee was moved into flexion. After a fatiguing protocol,

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. [6]	18–25 yo college athletes		Nm:			
		Extensors 60°/s	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. [43]	19–31 yo sedentary to elite athletes		ft lb/lb body weight:			
		Extensors 60°/s	89 ± 10	69 ± 14	29	Yes
		Flexors 60°/s	45 ± 7	37 ± 8	22	No
Lephart et al. [20]	College athletes		Nm:			
		Extensors 60°/s	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. [27]	20–28 yo recreational athletes		Nm/kg:			
		Extensors 180°/s	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 [17]	7–12 yo athletes		Nm:			
		7 yo, flexors/extensors 60°/s	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
yo year-old

Table 6.3 Gender differences in hamstrings-to-quadriceps ratio

			Results ratio %			
Study	Subject data	Testing protocol	Male	Female	Difference (%)	Difference significant?
Bowerman et al. [6]	18–25 yo college athletes	Flexion/extension, 60°/s	52.0 ± 8.5	52.4 ± 7.3	0	No
Rosene et al. [29]	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. [2]	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 [7]	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. [1]	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. [13]	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 [17]	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
yo year-old

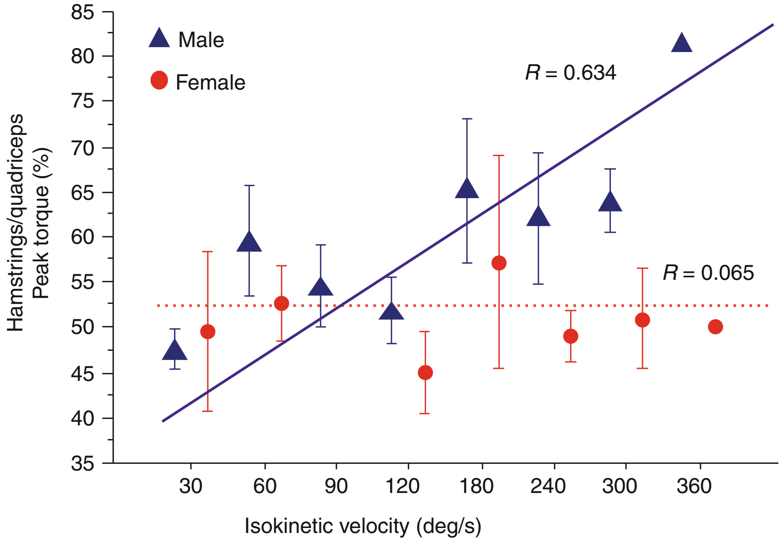


Fig. 6.1 Hamstrings-to-quadriceps ratio in female and male subjects diverges with increasing angular velocity [15] (Reprinted from Hewett et al. [15]; with permission from *Journal of Science and Medicine in Sport*, Elsevier Publishers)

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 [30].

A more integrated measure of proprioception may be accomplished through balance testing, which is variable across different sports and levels of competition [18]. In one study, female soccer athletes displayed significantly better balance than male athletes on a commercial balance platform [31]. A fatiguing protocol of maximal effort isokinetic knee flexion and extensions did not affect balance for either males or females [30]. 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 [5] which is an area of incomplete research [34]. 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 [5]. It should be noted that landing with this degree of trunk flexion would likely be prohibitive during athletic activities as it would probably lead to decrements in sport-specific performance.

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

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 [33]. In one study, 16 female high school volleyball players performed a drop jump from increasing heights

(15, 30, and 45 cm) [10]. 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, 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 [41]. 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.

Time to Peak Torque

Several authors (Table 6.4) have reported no significant differences in time to peak torque between male and female subjects [2, 6, 31]. Huston and Wojtys reported that the force output of elite athletes and nonathletic males and females tested isokinetically at either 60 or 240°/s showed no significant differences in time to peak torque in knee extension between athletes and nonathletes [19]. 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 net ball pass at chest level compared to females [8]. Electromyographic (EMG) outputs recorded for the quadriceps, hamstrings, and gastrocnemius showed that all muscle groups demonstrated prestop electrical activity, suggesting a preprogrammed 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 [8].

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 [23]. 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.

Summary

There are gender differences in neuromuscular indices such as laxity, stiffness, strength, 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.

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 [19]	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. [6]	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. [31]	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. [2]	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 [23]	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. [43]	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, *yo* year-old

References

1. Anderson AF, Dome DC, Gautam S et al (2001) Correlation of anthropometric measurements, strength, anterior cruciate ligament size, and intercondylar notch characteristics to sex differences in anterior cruciate ligament tear rates. Am J Sports Med 29(1):58–66
2. Barber-Westin SD, Galloway M, Noyes FR et al (2005) Assessment of lower limb neuromuscular control in prepubescent athletes. Am J Sports Med 33(12): 1853–1860
3. Barber-Westin SD, Noyes FR, Galloway M (2006) Jump-land characteristics and muscle strength development in young athletes: a gender comparison of 1140 athletes 9 to 17 years of age. Am J Sports Med 34(3):375–384
4. Blackburn JT, Riemann BL, Padua DA (2004) Sex comparison of extensibility, passive, and active stiffness of the knee flexors. Clin Biomech (Bristol, Avon) 19(1):36–43
5. Blackburn JT, Padua DA (2008) Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. Clin Biomech (Bristol, Avon) 23(3):313–319
6. Bowerman SJ, Smith DR, Carlson M et al (2006) A comparison of factors influencing ACL injury in male and female athletes and non-athletes. Phys Ther Sport 7(3):144–152
7. Buchanan PA, Vardaxis VG (2003) Sex-related and Age-related differences in knee strength of basketball players ages 11–17 years. J Athl Train 38(3):231–237
8. Cowling EJ, Steele JR (2001) The effect of upper-limb motion on lower-limb muscle synchrony. Implications for anterior cruciate ligament injury. J Bone Joint Surg Am 83-A(1):35–41
9. Delextrat A, Baker J, Cohen DD et al (2011) Effect of a simulated soccer match on the functional hamstrings-to-quadriceps ratio in amateur female players. Scand J Med Sci Sports. doi:10.1111/j.1600-0838.2011.01415.x.
10. Ford KR, Myer GD, Schmitt LC et al (2011) Preferential quadriceps activation in female athletes with incremental increases in landing intensity. J Appl Biomech 27(3):215–222
11. Granata KP, Padua DA, Wilson SE (2002) Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. J Electromyogr Kinesiol 12(2): 127–135
12. Granata KP, Wilson SE, Padua DA (2002) Gender differences in active musculoskeletal stiffness. Part I. Quantification in controlled measurements of knee joint dynamics. J Electromyogr Kinesiol 12(2):119–126
13. Hewett TE, Stroupe AL, Nance TA et al (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24(6):765–773
14. Hewett TE, Myer GD, Ford KR (2004) Decrease in neuromuscular control about the knee with maturation in female athletes. J Bone Joint Surg Am 86-A(8):1601–1608
15. 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
16. Hill AV (1953) The mechanics of active muscle. Proc R Soc Lond B Biol Sci 141(902):104–117
17. Holm I, Vollestad N (2008) Significant effect of gender on hamstring-to-quadriceps strength ratio and static balance in prepubescent children from 7 to 12 years of age. Am J Sports Med 36(10):2007–2013
18. Hrysomallis C (2011) Balance ability and athletic performance. Sports Med 41(3):221–232
19. Huston LJ, Wojtys EM (1996) Neuromuscular performance characteristics in elite female athletes. Am J Sports Med 24(4):427–436
20. Lephart SM, Ferris CM, Riemann BL et al (2002) Gender differences in strength and lower extremity kinematics during landing. Clin Orthop 401:162–169
21. Myer GD, Ford KR, Paterno MV et al (2008) The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. Am J Sports Med 36(6):1073–1080
22. Noyes FR, Grood ES, Torzilli PA (1989) Current concepts review. The definitions of terms for motion and position of the knee and injuries of the ligaments. J Bone Joint Surg Am 71(3):465–472
23. Noyes FR, Barber-Westin SD (2005) Isokinetic profile and differences in tibial rotation strength between male and female athletes 11 to 17 years of age. Isok Exer Sci 13:251–259
24. Nunome H, Asai T, Ikegami Y et al (2002) Three-dimensional kinetic analysis of side-foot and instep soccer kicks. Med Sci Sports Exerc 34(12):2028–2036
25. Oh YK, Kreinbrink JL, Wojtys EM et al (2012) Effect of axial tibial torque direction on ACL relative strain and strain rate in an in vitro simulated pivot landing. J Orthop Res 30(4):528–534
26. Park SK, Stefanyshyn DJ, Loitz-Ramage B et al (2009) Changing hormone levels during the menstrual cycle affect knee laxity and stiffness in healthy female subjects. Am J Sports Med 37(3):588–598
27. Pincivero DM, Gandaio CM, Ito Y (2003) Gender-specific knee extensor torque, flexor torque, and muscle fatigue responses during maximal effort contractions. Eur J Appl Physiol 89(2):134–141
28. Renstrom P, Ljungqvist A, Arendt E et al (2008) Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. Br J Sports Med 42(6):394–412
29. Rosene JM, Fogarty TD, Mahaffey BL (2001) Isokinetic hamstrings: quadriceps ratios in intercollegiate athletes. J Athl Train 36(4):378–383
30. Rozzi SL, Lephart SM, Fu FH (1999) Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. J Athl Train 34(2):106–114
31. Rozzi SL, Lephart SM, Gear WS et al (1999) Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. Am J Sports Med 27(3):312–319

32. Sangnier S, Tourny-Chollet C (2007) Comparison of the decrease in strength between hamstrings and quadriceps during isokinetic fatigue testing in semiprofessional soccer players. Int J Sports Med 28(11):952–957
33. Shultz SJ, Perrin DH, Adams MJ et al (2001) Neuromuscular response characteristics in men and women after knee perturbation in a single-leg, weight-bearing stance. J Athl Train 36(1):37–43
34. Shultz SJ, Schmitz RJ, Nguyen AD (2008) Research retreat IV: ACL injuries–the gender bias: April 3–5, 2008 Greensboro, NC. J Athl Train 43(5):530–531
35. Shultz SJ, Schmitz RJ, Nguyen AD et al (2010) ACL research retreat V: an update on ACL injury risk and prevention, March 25–27, 2010, Greensboro, NC. J Athl Train 45(5):499–508
36. Shultz SJ, Schmitz RJ, Beynnon BD (2011) Variations in varus/valgus and internal/external rotational knee laxity and stiffness across the menstrual cycle. J Orthop Res 29(3):318–325
37. Small K, McNaughton L, Greig M et al (2010) The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. J Sci Med Sport 13(1):120–125
38. Steiner ME, Grana WA, Chillag K et al (1986) The effect of exercise on anterior-posterior knee laxity. Am J Sports Med 14(1):24–29
39. Uhorchak JM, Scoville CR, Williams GN et al (2003) Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets. Am J Sports Med 31(6):831–842
40. Winter DA (1983) Moments of force and mechanical power in jogging. J Biomech 16(1):91–97
41. Withrow TJ, Huston LJ, Wojtys EM et al (2006) The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. Am J Sports Med 34(2):269–274
42. Wojtys EM, Wylie BB, Huston LJ (1996) The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. Am J Sports Med 24(5):615–621
43. Wojtys EM, Ashton-Miller JA, Huston LJ (2002) A gender-related difference in the contribution of the knee musculature to sagittal-plane shear stiffness in subjects with similar knee laxity. J Bone Joint Surg Am 84-A(1):10–16
44. Wojtys EM, Huston LJ, Schock HJ et al (2003) Gender differences in muscular protection of the knee in torsion in size-matched athletes. J Bone Joint Surg Am 85-A(5):782–789
45. Zazulak BT, Paterno M, Myer GD et al (2006) The effects of the menstrual cycle on anterior knee laxity: a systematic review. Sports Med 36(10):847–862
46. Zebis MK, Andersen LL, Ellingsgaard H (2011) Rapid hamstring/quadriceps force capacity in male vs. female elite soccer players. J Strength Cond Res 25(7):1989–1993
47. Zech A, Hubscher M, Vogt L et al (2010) Balance training for neuromuscular control and performance enhancement: a systematic review. J Athl Train 45(4):392–403

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

7

Ajit M.W. Chaudhari, Laura C. Schmitt, and Thomas P. Andriacchi

Contents

A.M.W. Chaudhari, Ph.D. (✉)
Department of Orthopaedics, Sports Health & Performance Institute, Ohio State University Sports Medicine Center,
2050 Kenny Rd, Suite 3100, Columbus, OH 43221, USA
e-mail: chaudhari.2@osu.edu

L.C. Schmitt, Ph.D., P.T.
Ohio State University School of Health & Rehabilitation Sciences, 516 Atwell Hall, 453 W. 10th Ave, Columbus, OH 43210, USA
e-mail: laura.schmitt@osumc.edu

T.P. Andriacchi, Ph.D.
Biomechanical Engineering Division, Stanford University, Durand Building #227, Stanford, CA 94305-4038, USA
e-mail: tandriac@Stanford.edu

Introduction

Tibiofemoral osteoarthritis (OA) occurs in a substantial and continually increasing portion of men and women who are greater than 50 years of age [43, 58]. 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 [19, 37, 51, 52, 77]. 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 [51, 77]. 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 that underwent reconstruction versus those treated conservatively [51, 77]. 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 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 %) [55]. Only 4 % of the contralateral knees showed radiographic OA. Recently, 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 [59]. Across various study methodologies and operational definitions, the findings from these

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_7, © Springer-Verlag Berlin Heidelberg 2012

studies highlight the significance of the development of knee OA after ACL injury. Despite the significance of early development of post-traumatic knee OA, the details of its early development are not well understood and few modifiable risk factors have been identified [15]. As discussed in Chap. 3, concomitant meniscal injury requiring a meniscectomy is known to have a detrimental effect as well. 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 [3].

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 [5, 33, 46], whereas degenerative changes in cartilage and other joint structures are observed years following the injury [19, 37, 51, 52, 77]. 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 contributes to degradation of the meniscus and articular cartilage [5, 33, 46, 64, 65].

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 post-traumatic 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.

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 [5, 33]. 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 [5, 33]. Specifically, Andriacchi and Dyrby [5] found that the magnitude of the internal rotational offset correlated with the magnitude of the 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. These observed offsets in motion have been corroborated by studies of other activities using radiographic techniques, including stereoradiography [72], fluoroscopy [21], and magnetic resonance imaging (MRI) [9, 50, 66]. 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 [65, 72]. 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 [57]. This pattern is similar to kinematic changes in ACL-reconstructed subjects [65, 72]. To date, it remains unknown how meniscectomy interacts with ACL reconstruction in altering these kinematics.

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 [32] and internal rotation [54] of the tibia on the femur. Failure to restore anatomic obliquity of the graft in femoral tunnel placement (Fig. 7.1) can result in a knee with adequate sagittal stability but inadequate rotational stability [10, 70]. Abebe et al. [1] 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 [63, 64] 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. [64] 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. Graft placement, muscle function, and tibiofemoral kinematics likely interact in a manner that precipitates cartilage degradation in the ACL-deficient and ACL-reconstructed knee.

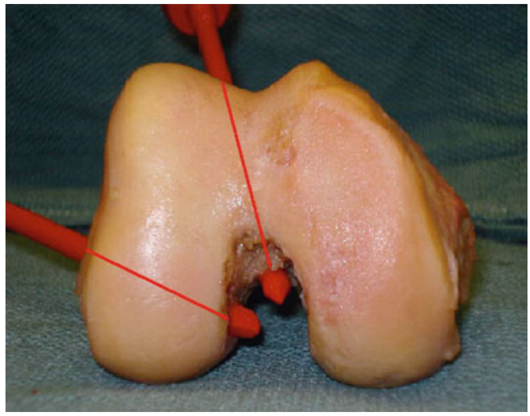


Fig. 7.1 Notch view of a dissected femoral specimen showing range of coronal obliquity between vertical and maximally oblique femoral tunnels (Reproduced with permission from Bedi et al. [10])

Critical Points

- Evidence during activities of daily living indicates 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.

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 [35, 71, 76] and are informative of the metabolic changes that are associated with ACL injury [49, 60, 81]. 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 [49, 60, 81]. 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 [35, 60, 76, 81]. 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.

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 [27, 67, 82]. This imbalance in compressive load between medial and lateral compartments can be approximated by the knee adduction moment [67]. 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. 7.2). In the healthy knee, there is a positive relationship between the knee adduction moment and the thickness of the medial femoral cartilage [7]. Specifically, the higher the proportion of the compressive load that is borne by the medial femoral compartment, the thicker the medial femoral cartilage [4]. 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 [41, 45, 67]. 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 [47, 73, 74].

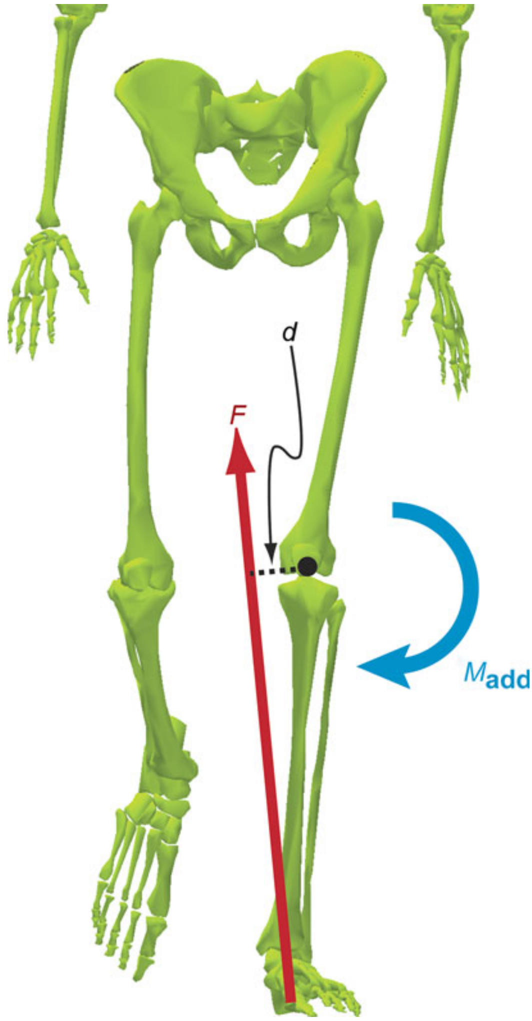


Fig. 7.2 Illustration of the knee adduction moment. The ground reaction force vector (*F*) passes medially to the knee joint center with moment arm *d*, resulting in an external knee adduction moment (M_{add}). As the moment arm of the ground reaction force increases, the load on the medial compartment increases relative to the lateral compartment.

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 [17, 20, 22, 23, 26, 28, 36, 40, 44, 68, 69]. The chondrocytes proliferate in response to dynamic hydrostatic compression and create additional extracellular matrix components, such as proteoglycans and type II collagen [44]. In response to shear stresses, proteoglycan production increases, while the expression of matrix metalloproteinases declines [20, 68, 69]. Finally, an increased load causes chondrocytes to respond by changing their volume and aspect ratio [30, 68].

Cartilage tissue explants exposed to compression also demonstrate increased proteoglycan deposition [14, 61, 80]. Alterations to the cytoskeleton appear to vary according to the magnitude of compression [24], although the response to compression is not consistent across the cartilage [12] 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 [80], proximity to chondrocytes [61], and changes in fluid flow [14], as well as the origin of the explant from the articular surface [12].

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 [75] and dogs [11, 39] 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 [11]. 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 [39] or by the immobilization of a contralateral limb [38].

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 [8, 13, 18]. In addition, the chondrocytes are larger and rounder [13, 48, 62]. 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 [8, 13, 18, 25]. 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 [74]. 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.

Kinematic Pathway to Osteoarthritis After ACL Rupture

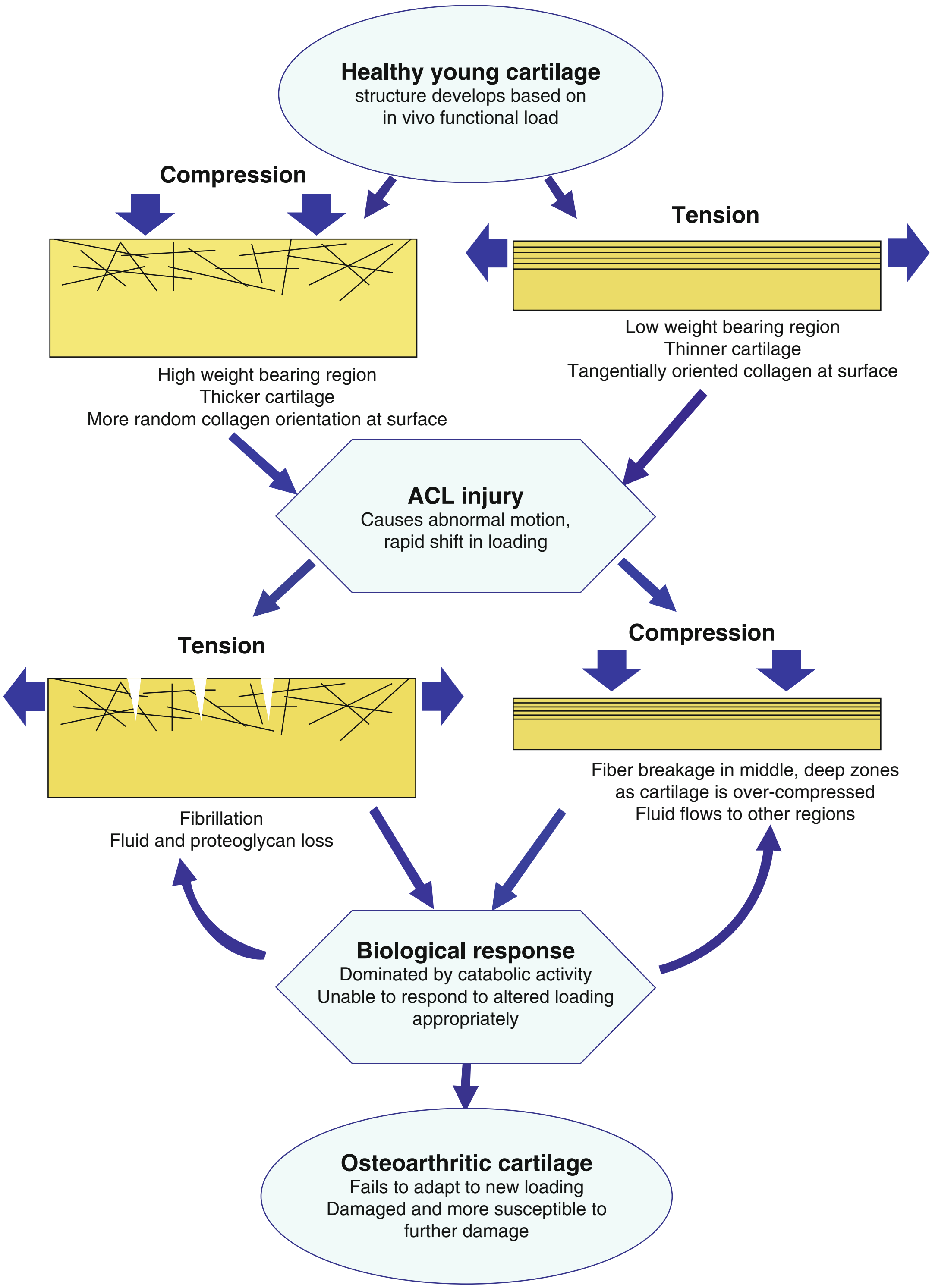
The kinematic and degenerative changes affecting the knee joint after ACL rupture, in conjunction with the response of cartilage to loading at the cellular and tissue level, support a mechanism of initiation of OA after ACL injury. The change in knee motion caused by ACL injury results in shifts in regions 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 [2]. 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 [42]. 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 [8, 13, 14, 18, 79, 80] and the ramifications of changes to loading on the health of the cartilage (Fig. 7.3). The central regions undergo the highest compressive loads [2, 56]. 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 section "Interaction Between Kinematics, Cartilage Metabolism, and Cartilage Structure"), the peripheral regions are thinner, with a better-defined superficial layer containing greater tangential collagen fiber orientation [8, 13, 18]. Conversely, the central regions show increased thickness and a less-organized superficial layer of collagen [8, 13, 18].

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 [11, 38, 74, 75] 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 [34, 35, 44, 53]. 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 [29, 78]. Tangential surface traction and associated shear stress within the cartilage lead to upregulation of catabolic factors, such as matrix metalloproteinase and interleukins [20, 31, 60]. The relationship between all

Fig. 7.3 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 breakdown as well as catabolic biological responses, initiating the pathway to osteoarthritis (Reproduced with permission from Chaudhari et al. [16])


Healthy young cartilage
structure develops based on
in vivo functional load
Compression
Tension
High weight bearing region
Thicker cartilage
More random collagen orientation at surface
Low weight bearing region
Thinner cartilage
Tangentially oriented collagen at surface
ACL injury
Causes abnormal motion,
rapid shift in loading
Tension
Compression
Fibrillation
Fluid and proteoglycan loss
Fiber breakage in middle, deep zones
as cartilage is over-compressed
Fluid flows to other regions
Biological response
Dominated by catabolic activity
Unable to respond to altered loading
appropriately
Osteoarthritic cartilage
Fails to adapt to new loading
Damaged and more susceptible to
further damage

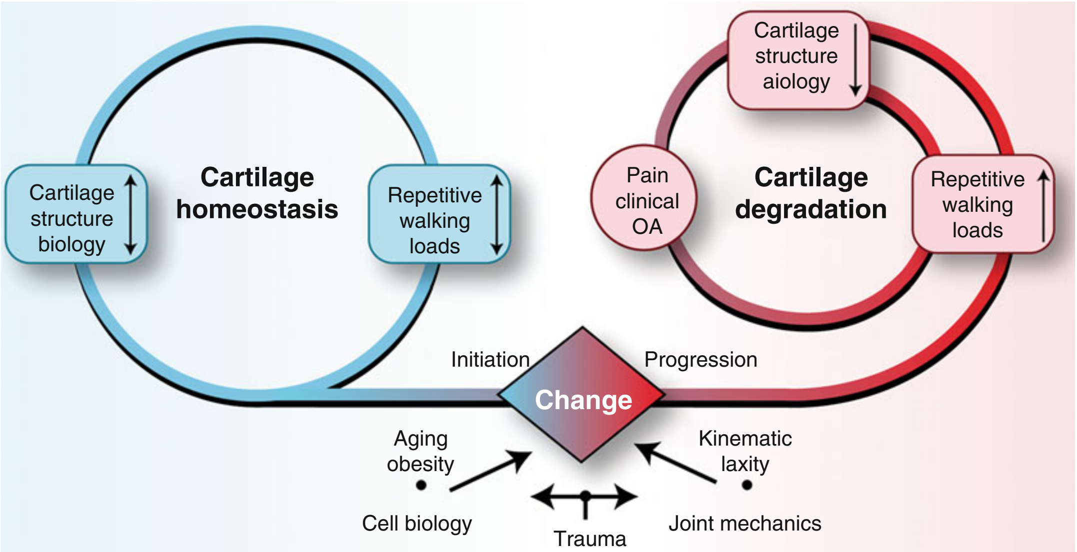


Fig. 7.4 Healthy cartilage homeostasis is maintained by the magnitude of the repetitive cyclic loads during walking, and cartilage is thicker in regions with higher loads during walking. The initiation of osteoarthritis (*OA*) is associated with a change (due to injury, increased laxity, neuromuscular 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. [7])

of these factors in the wake of the initiation of increased frictional forces creates a cycle (Fig. 7.4). Increased tangential forces lead to fibrillation and catabolic activity, which in turn lead to increased friction. 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 [4, 6].

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 is 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.

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 post 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 aid in the development of techniques to prevent the initiation and progression of OA in the ACL-injured population.

Acknowledgment The authors would like to thank Maurice Manring, Ph.D. for his editorial assistance with this manuscript.

References

1. Abebe ES, Utturkar GM, Taylor DC et al (2011) The effects of femoral graft placement on in vivo knee kinematics after anterior cruciate ligament reconstruction. J Biomech 44(5):924–929
2. Ahmed AM, Burke DL (1983) In-vitro measurement of static pressure distribution in synovial joints – part I: tibial surface of the knee. J Biomech Eng 105(3): 216–225
3. Ait Si Selmi T, Fithian D, Neyret P (2006) The evolution of osteoarthritis in 103 patients with ACL reconstruction at 17 years follow-up. Knee 13(5):353–358
4. Andriacchi TP, Mundermann A, Smith RL et al (2004) A framework for the in vivo pathomechanics of osteoarthritis at the knee. Ann Biomed Eng 32(3): 447–457
5. Andriacchi TP, Dyrby CO (2005) Interactions between kinematics and loading during walking for the normal and ACL deficient knee. J Biomech 38(2):293–298
6. Andriacchi TP, Mundermann A (2006) The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. Curr Opin Rheumatol 18(5):514–518
7. Andriacchi TP, Koo S, Scanlan SF (2009) Gait mechanics influence healthy cartilage morphology and osteoarthritis of the knee. J Bone Joint Surg Am 91(Suppl 1): 95–101
8. Appleyard RC, Burkhardt D, Ghosh P et al (2003) Topographical analysis of the structural, biochemical and dynamic biomechanical properties of cartilage in an ovine model of osteoarthritis. Osteoarthritis Cartilage 11(1):65–77
9. Barrance PJ, Williams GN, Snyder-Mackler L et al (2006) Altered knee kinematics in ACL-deficient non-copers: a comparison using dynamic MRI. J Orthop Res 24(2):132–140
10. Bedi A, Raphael B, Maderazo A et al (2010) Transtibial versus anteromedial portal drilling for anterior cruciate ligament reconstruction: a cadaveric study of femoral tunnel length and obliquity. Arthroscopy 26(3):342–350
11. Behrens F, Kraft EL, Oegema TR Jr (1989) Biochemical changes in articular cartilage after joint immobilization by casting or external fixation. J Orthop Res 7(3):335–343
12. Bevill SL, Briant PL, Levenston ME et al (2009) Central and peripheral region tibial plateau chondrocytes respond differently to in vitro dynamic compression. Osteoarthritis Cartilage 17(8):980–987
13. Bullough PG, Yawitz PS, Tafra L et al (1985) Topographical variations in the morphology and biochemistry of adult canine tibial plateau articular cartilage. J Orthop Res 3(1):1–16
14. Buschmann MD, Kim YJ, Wong M et al (1999) Stimulation of aggrecan synthesis in cartilage explants by cyclic loading is localized to regions of high interstitial fluid flow. Arch Biochem Biophys 366(1):1–7
15. Chaganti RK, Lane NE (2011) Risk factors for incident osteoarthritis of the hip and knee. Curr Rev Musculoskelet Med 4(3):99–104
16. Chaudhari AM, Briant PL, Bevill SL et al (2008) Knee kinematics, cartilage morphology, and osteoarthritis after ACL injury. Med Sci Sports Exerc 40(2):215–222
17. Chowdhury TT, Bader DL, Lee DA (2006) Dynamic compression counteracts IL-1beta induced iNOS and COX-2 activity by human chondrocytes cultured in agarose constructs. Biorheology 43(3–4):413–429
18. Clark JM (1991) Variation of collagen fiber alignment in a joint surface: a scanning electron microscope study of the tibial plateau in dog, rabbit, and man. J Orthop Res 9(2):246–257
19. Daniel DM, Stone ML, Dobson BE et al (1994) Fate of the ACL-injured patient. A prospective outcome study. Am J Sports Med 22(5):632–644
20. Das P, Schurman DJ, Smith RL (1997) Nitric oxide and G proteins mediate the response of bovine articular chondrocytes to fluid-induced shear. J Orthop Res 15(1):87–93
21. Defrate LE, Papannagari R, Gill TJ et al (2006) The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency: an in vivo imaging analysis. Am J Sports Med 34(8):1240–1246
22. Deschner J, Hofman CR, Piesco NP et al (2003) Signal transduction by mechanical strain in chondrocytes. Curr Opin Clin Nutr Metab Care 6(3):289–293
23. Deschner J, Rath-Deschner B, Agarwal S (2006) Regulation of matrix metalloproteinase expression by dynamic tensile strain in rat fibrochondrocytes. Osteoarthritis Cartilage 14(3):264–272
24. Durrant LA, Archer CW, Benjamin M et al (1999) Organisation of the chondrocyte cytoskeleton and its response to changing mechanical conditions in organ culture. J Anat 194(Pt 3):343–353

25. Eggli PS, Hunziker EB, Schenk RK (1988) Quantitation of structural features characterizing weight- and less-weight-bearing regions in articular cartilage: a stereological analysis of medial femoral condyles in young adult rabbits. Anat Rec 222(3):217–227
26. Elder SH, Goldstein SA, Kimura JH et al (2001) Chondrocyte differentiation is modulated by frequency and duration of cyclic compressive loading. Ann Biomed Eng 29(6):476–482
27. Erhart JC, Dyrby CO, D'Lima DD et al (2010) Changes in in vivo knee loading with a variable-stiffness intervention shoe correlate with changes in the knee adduction moment. J Orthop Res 28(12):1548–1553
28. Fedewa MM, Oegema TR Jr, Schwartz MH et al (1998) Chondrocytes in culture produce a mechanically functional tissue. J Orthop Res 16(2):227–236
29. Forster H, Fisher J (1999) The influence of continuous sliding and subsequent surface wear on the friction of articular cartilage. Proc Inst Mech Eng H 213(4):329–345
30. Freeman PM, Natarajan RN, Kimura JH et al (1994) Chondrocyte cells respond mechanically to compressive loads. J Orthop Res 12(3):311–320
31. Fujisawa T, Hattori T, Takahashi K et al (1999) Cyclic mechanical stress induces extracellular matrix degradation in cultured chondrocytes via gene expression of matrix metalloproteinases and interleukin-1. J Biochem 125(5):966–975
32. Fukubayashi T, Torzilli PA, Sherman MF (1982) An in vitro biomechanical evaluation of anterior-posterior motion of the knee. Tibial displacement, rotation, and torque. J Bone Joint Surg Am 64A(2):258–264
33. Georgoulis AD, Papadonikolakis A, Papageorgiou CD et al (2003) Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking. Am J Sports Med 31(1):75–79
34. Guilak F, Ratcliffe A, Lane N et al (1994) Mechanical and biochemical changes in the superficial zone of articular cartilage in canine experimental osteoarthritis. J Orthop Res 12(4):474–484
35. Hasler EM, Herzog W, Leonard TR et al (1998) In vivo knee joint loading and kinematics before and after ACL transection in an animal model. J Biomech 31(3):253–262
36. Ikenoue T, Trindade MC, Lee MS et al (2003) Mechanoregulation of human articular chondrocyte aggrecan and type II collagen expression by intermittent hydrostatic pressure in vitro. J Orthop Res 21(1):110–116
37. Kannus P, Jarvinen M (1989) Posttraumatic anterior cruciate ligament insufficiency as a cause of osteoarthritis in a knee joint. Clin Rheumatol 8(2):251–260
38. Kiviranta I, Jurvelin J, Tammi M et al (1987) Weight bearing controls glycosaminoglycan concentration and articular cartilage thickness in the knee joints of young beagle dogs. Arthritis Rheum 30(7):801–809
39. Kiviranta I, Tammi M, Jurvelin J et al (1988) Moderate running exercise augments glycosaminoglycans and thickness of articular cartilage in the knee joint of young beagle dogs. J Orthop Res 6(2):188–195
40. Knight MM, Ross JM, Sherwin AF et al (2001) Chondrocyte deformation within mechanically and enzymatically extracted chondrons compressed in agarose. Biochim Biophys Acta 1526(2):141–146
41. Koo S, Andriacchi TP (2007) A comparison of the influence of global functional loads vs. local contact anatomy on articular cartilage thickness at the knee. J Biomech 40(13):2961–2966
42. Koo S, Andriacchi TP (2008) The knee joint center of rotation is predominantly on the lateral side during normal walking. J Biomech 41(6):1269–1273
43. Kumm JA, Tamm, Lintrop M et al (2011) The prevalence and progression of radiographic knee osteoarthritis over 6 years in a population-based cohort of middle-aged subjects. Rheumatol Int. http://www.ncbi.nlm.nih.gov/pubmed/22083615. Epub ahead of print, Nov 16, 2011. DOI: 10.1007/s00296-011-2221-3
44. Lee DA, Bader DL (1997) Compressive strains at physiological frequencies influence the metabolism of chondrocytes seeded in agarose. J Orthop Res 15(2):181–188
45. Li G, Park SE, DeFrate LE (2005) The cartilage thickness distribution in the tibiofemoral joint and its correlation with cartilage-to-cartilage contact. Clin Biomech (Bristol, Avon) 20(7):736–744
46. Li G, Moses JM, Papannagari R et al (2006) Anterior cruciate ligament deficiency alters the in vivo motion of the tibiofemoral cartilage contact points in both the anteroposterior and mediolateral directions. J Bone Joint Surg Am 88(8):1826–1834
47. Liphardt AM, Mundermann A, Koo S et al (2009) Vibration training intervention to maintain cartilage thickness and serum concentrations of cartilage oligometric matrix protein (COMP) during immobilization. Osteoarthritis Cartilage 17(12):1598–1603
48. Little CB, Ghosh P (1997) Variation in proteoglycan metabolism by articular chondrocytes in different joint regions is determined by post-natal mechanical loading. Osteoarthritis Cartilage 5(1):49–62
49. Liu W, Burton-Wurster N, Glant TT et al (2003) Spontaneous and experimental osteoarthritis in dog: similarities and differences in proteoglycan levels. J Orthop Res 21(4):730–737
50. Logan MC, Williams A, Lavelle J et al (2004) Tibiofemoral kinematics following successful anterior cruciate ligament reconstruction using dynamic multiple resonance imaging. Am J Sports Med 32(4):984–992
51. Lohmander LS, Ostenberg A, Englund M et al (2004) High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum 50(10):3145–3152
52. Maletius W, Messner K (1999) Eighteen- to twenty-four-year follow-up after complete rupture of the anterior cruciate ligament. Am J Sports Med 27(6):711–717
53. Maniwa S, Nishikori T, Furukawa S et al (2001) Alteration of collagen network and negative charge of articular cartilage surface in the early stage of

experimental osteoarthritis. Arch Orthop Trauma Surg 121(4):181–185
54. Markolf KL, Mensch JS, Amstutz HC (1976) Stiffness and laxity of the knee – the contributions of the supporting structures. A quantitative in vitro study. J Bone Joint Surg Am 58(5):583–594
55. Meuffels DE, Favejee MM, Vissers MM et al (2009) Ten year follow-up study comparing conservative versus operative treatment of anterior cruciate ligament ruptures. A matched-pair analysis of high level athletes. Br J Sports Med 43(5):347–351
56. Mow VC, Kuei SC, Lai WM et al (1980) Biphasic creep and stress relaxation of articular cartilage in compression? Theory and experiments. J Biomech Eng 102(1):73–84
57. Netravali NA, Giori NJ, Andriacchi TP (2010) Partial medial meniscectomy and rotational differences at the knee during walking. J Biomech 43(15):2948–2953
58. Nguyen US, Zhang Y, Zhu Y et al (2011) Increasing prevalence of knee pain and symptomatic knee osteoarthritis: survey and cohort data. Ann Intern Med 155(11):725–732
59. Oiestad BE, Holm I, Aune AK et al (2010) Knee function and prevalence of knee osteoarthritis after anterior cruciate ligament reconstruction: a prospective study with 10 to 15 years of follow-up. Am J Sports Med 38(11):2201–2210
60. Pelletier JP, Mineau F, Faure MP et al (1990) Imbalance between the mechanisms of activation and inhibition of metalloproteases in the early lesions of experimental osteoarthritis. Arthritis Rheum 33(10):1466–1476
61. Quinn TM, Grodzinsky AJ, Buschmann MD et al (1998) Mechanical compression alters proteoglycan deposition and matrix deformation around individual cells in cartilage explants. J Cell Sci 111(Pt 5):573–583
62. Quinn TM, Hunziker EB, Hauselmann HJ (2005) Variation of cell and matrix morphologies in articular cartilage among locations in the adult human knee. Osteoarthritis Cartilage 13(8):672–678
63. Ristanis S, Stergiou N, Siarava E et al (2009) Effect of femoral tunnel placement for reconstruction of the anterior cruciate ligament on tibial rotation. J Bone Joint Surg Am 91(9):2151–2158
64. Scanlan SF, Blazek K, Chaudhari AM et al (2009) Graft orientation influences the knee flexion moment during walking in patients with anterior cruciate ligament reconstruction. Am J Sports Med 37(11):2173–2178
65. Scanlan SF, Chaudhari AM, Dyrby CO et al (2010) Differences in tibial rotation during walking in ACL reconstructed and healthy contralateral knees. J Biomech 43(9):1817–1822
66. Scarvell JM, Smith PN, Refshauge KM et al (2005) Comparison of kinematics in the healthy and ACL injured knee using MRI. J Biomech 38(2):255–262
67. Schipplein OD, Andriacchi TP (1991) Interaction between active and passive knee stabilizers during level walking. J Orthop Res 9(1):113–119
68. Smith RL, Donlon BS, Gupta MK et al (1995) Effects of fluid-induced shear on articular chondrocyte morphology and metabolism in vitro. J Orthop Res 13(6):824–831
69. Smith RL, Trindade MC, Ikenoue T et al (2000) Effects of shear stress on articular chondrocyte metabolism. Biorheology 37(1):95–107
70. Sohn DH, Garrett WE Jr (2009) Transitioning to anatomic anterior cruciate ligament graft placement. J Knee Surg 22(2):155–160
71. Tashman S, Anderst W, Kolowich P et al (2004) Kinematics of the ACL-deficient canine knee during gait: serial changes over two years. J Orthop Res 22(5):931–941
72. Tashman S, Collon D, Anderson K et al (2004) Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am J Sports Med 32(4):975–983
73. Vanwanseele B, Eckstein F, Knecht H et al (2002) Knee cartilage of spinal cord-injured patients displays progressive thinning in the absence of normal joint loading and movement. Arthritis Rheum 46(8): 2073–2078
74. Vanwanseele B, Eckstein F, Knecht H et al (2003) Longitudinal analysis of cartilage atrophy in the knees of patients with spinal cord injury. Arthritis Rheum 48(12):3377–3381
75. Videman T (1982) Experimental osteoarthritis in the rabbit: comparison of different periods of repeated immobilization. Acta Orthop Scand 53(3):339–347
76. Vilensky JA, O'Connor BL, Brandt KD et al (1994) Serial kinematic analysis of the unstable knee after transection of the anterior cruciate ligament: temporal and angular changes in a canine model of osteoarthritis. J Orthop Res 12(2):229–237
77. von Porat A, Roos EM, Roos H (2004) High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. Ann Rheum Dis 63(3):269–273
78. Wang H, Ateshian GA (1997) The normal stress effect and equilibrium friction coefficient of articular cartilage under steady frictional shear. J Biomech 30(8): 771–776
79. Wilson W, Driessen NJ, van Donkelaar CC et al (2006) Prediction of collagen orientation in articular cartilage by a collagen remodeling algorithm. Osteoarthritis Cartilage 14(11):1196–1202
80. Wong M, Wuethrich P, Buschmann MD et al (1997) Chondrocyte biosynthesis correlates with local tissue strain in statically compressed adult articular cartilage. J Orthop Res 15(2):189–196
81. Yoshioka M, Coutts RD, Amiel D et al (1996) Characterization of a model of osteoarthritis in the rabbit knee. Osteoarthritis Cartilage 4(2):87–98
82. Zhao D, Banks SA, Mitchell KH et al (2007) Correlation between the knee adduction torque and medial contact force for a variety of gait patterns. J Orthop Res 25(6):789–797

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

8

William P. Ebben

Contents

Introduction

The etiology of anterior cruciate ligament (ACL) injuries includes a variety of intrinsic and extrinsic factors [27]. Intrinsic factors include hormonal issues, lower limb alignment, intercondylar notch size, ACL size, and joint laxity [27, 30]. These intrinsic factors may be gender-specific and not modifiable [27]. In addition to these intrinsic factors, there exist a variety of extrinsic factors such as the type of sport played, environmental conditions, equipment, and athlete strength and conditioning. Of these factors, athlete strength and conditioning is an area where sports medicine and strength and conditioning professionals may be most able to intervene to reduce ACL injuries [27].

Athlete conditioning includes training the timing, magnitude, and patterns of neuromuscular recruitment in order to optimize the ability of muscle and connective tissue to produce less stress on the knee joint and to potentially provide protection

W.P. Ebben, Ph.D.
Department of Health, Exercise Science, and Sport Management, University of Wisconsin – Parkside, Kenosha, WI 53144, USA
e-mail: webben70@hotmail.com

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_8, © Springer-Verlag Berlin Heidelberg 2012

from injury. 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 [27, 30, 36]. Thus, priority should be given to understanding the role of timing and magnitude of muscle activation during movements which are most likely to produce injury, including dynamic tasks such as running, cutting, and jumping. Ultimately, in the prevention of ACL injuries, neuromuscular training may be the best option available. Programs designed to prevent ACL injuries often focus on training the neuromuscular system in order to improve hamstring-to-quadriceps ratios, lower limb biomechanics such as abduction/adduction moments, hip alignment, dynamic balance, and fatigue resistance [1, 41]. For example, hamstring fatigue is associated with a 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 [41]. Not surprisingly, evidence shows that neuromuscular training has been shown to reduce injury, potentially through reduced fatigue among other factors [1, 29]. In order to maximize the potential for neuromuscular training to reduce the incidence of ACL injuries, a comprehensive assessment of the biomechanics of these injuries and 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

- Gender differences in muscle activation patterns are present during running, jumping, 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.

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 many different dynamic movements such as running, cutting, and jumping. Muscle activation has been studied during these movements because they have been implicated as part of the etiology of ACL injuries [1, 27, 30].

Surface EMG has been commonly used and found to be reliable for assessing muscle activation and timing during running [57], cutting maneuvers [20], and jump landings [20]. EMG assesses the magnitude of muscle activation before and after foot contact. In addition to evaluating the magnitude of muscle activation, the timing of muscle activation has been studied before and after foot contact. Both the magnitude and timing of activation are believed to be important for knee joint stability and ACL injury prevention [1, 14, 27, 30, 36, 41, 58].

A variety of muscles have been studied including the gastrocnemius, tibialis anterior, gluteus medius, and the lateral and medial hamstrings, which include the biceps femoris and combination of semitendinosus and semimembranosus, respectively. 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 purposes of this chapter, muscles that cross the articulation of the acetabulum and femur, which is often referred to 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 bone, such as "tibial internal rotation." To the degree possible, these differences in descriptions will be clarified, and the joint movement will be described in terms of 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, consideration must be afforded to the biomechanics of these types of movements as well. Biomechanical factors such as the kinetics and kinematics of these types of 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 is the best option available to clinicians to remediate some of 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 that occurs during these dynamic activities.

It is important to note that 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 pictures 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, 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 force associated with running, jumping and landing, and cutting influence muscle activation.
- Research has been conducted most often with fit young adults and occasionally adolescents and young adult athletes.

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. The movements and forces that affect the ACL are most likely to occur shortly after foot contact during athletic movements [58]. Research shows that during the initial 40 % of the stance phase of cutting movements, women compared to men have less flexible coordination movement patterns, as evidenced by greater variability in interlimb segment and joint coupling, assessed with three-dimensional kinematics [51]. During the initial stance phase, peak ACL length has been shown to be the greatest, corresponding to approximately 50 ms after foot contact, which then decreases with knee flexion during landing [58]. 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 when the athlete is running, cutting, or jumping.

Sagittal Plane Mechanics

Although some researchers found limited gender disparity in sagittal plane biomechanical factors, the majority of investigations assessing this issue have reported differences. For example, one study found that there were no gender differences in knee flexion angle during unanticipated cutting after a jump stop [21]. Other investigators have reported that the quadriceps contribution to anterior shear of the tibia is thought to be maximal when the knee is flexed to <30° [30] and that the length of the ACL decreases with increased knee flexion angle on a drop jump [58]. This belief is supported by research showing that the greatest ACL loading occurs at 22.0° of flexion for men and 24.9° for women on a stop-jump task [36]. Figures 8.1 and 8.2 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 compared to men produce less hip and knee flexion [38], which likely increases the quadriceps role in ACL loading for women. Muscles crossing the knee and ankle may play an important role in dynamic stabilization of the ACL in the sagittal plane and help prevent ACL injury [30]. Thus, the muscle activation patterns of the hamstrings as well as the gastrocnemius are important for knee joint stabilization, particularly during fatigue conditions [30]. However, some evidence suggests that sagittal plane kinetics alone is insufficient to rupture the ACL. Dynamic musculoskeletal modeling of subjects during side-step cutting reveals that anterior drawer forces are not high enough to rupture the ACL [37], with quadriceps muscles producing only approximately half of the anterior tibial shear force required to induce ACL rupture [14]. Thus, undesirable muscular forces associated with sagittal plane biomechanics may comprise only part of the etiology of ACL injuries.

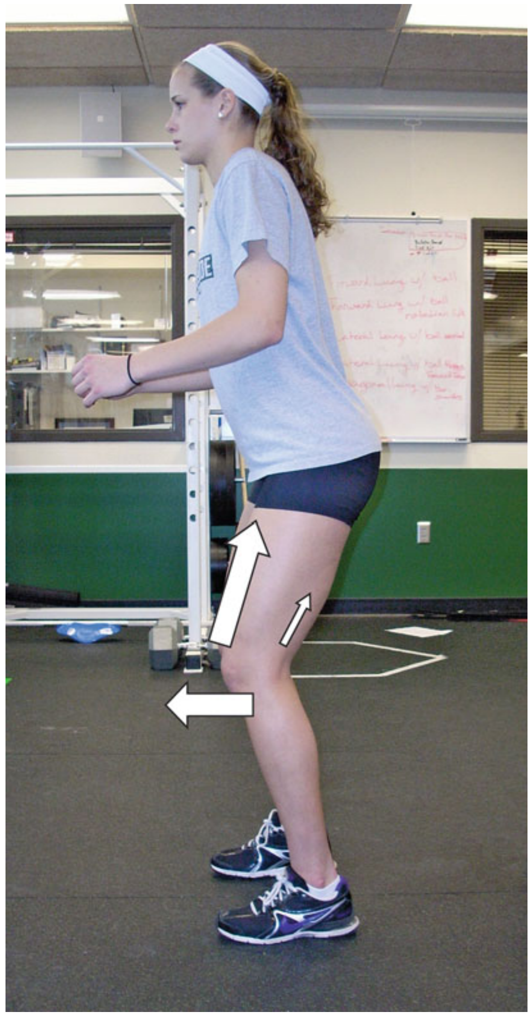


Fig. 8.1 Sagittal plane view of landing with vectors representing a large quadriceps force, limited hamstring force, and anterior tibial translation

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. [30] reviewed the role of increased knee valgus in increasing ACL strain. During knee valgus, medial femoral condyle lift-off and lateral femoral condyle compression occur, which in turn loads the ACL [30]. More specifically, the mechanics of injury during knee valgus have been speculated by some to be ACL impingement against the lateral wall of the intercondylar notch [50], 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

Fig. 8.2 Sagittal plane view of a desirable landing position

loads alone have been shown to be high enough to rupture the ACL. These levels of loads occur more commonly with women than men [37].

Compared to males, females have higher knee valgus angles and greater variability in knee valgus during side-step cutting [38]. Gender differences are characterized by women having greater ankle eversion [21, 33] and hip adduction [33, 38], both of which contribute to the valgus knee condition [33]. Additionally, females demonstrate higher frontal plane angular velocity at the knee, indicating they collapse into valgus more rapidly than males [33]. Concerns such as these apply to adolescent females who demonstrate greater knee valgus angles at initial contact compared to adolescent males [21]. Even among older and more highly trained subjects such as collegiate basketball players, women have more knee valgus than men during side-step cutting movements [39]. In addition to frontal plane biomechanics at the knee, females demonstrate greater ankle eversion and less inversion during unanticipated cutting after a jump stop [21], along with frontal plane differences represented by greater foot pronation angles during side-step cutting [38]. Figures 8.3 and 8.4 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.

Transverse Plane Mechanics

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, though some of the details remain uncertain. Sources suggest that increased internal hip rotation may potentiate ACL strain, noting that women have increased internal hip rotation compared to men during foot contact [30]. Others show women have less hip and knee internal rotation during side-step cutting than men [38]. 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 [46]. Other evidence shows that noncontact ACL injuries occur with, or may be exacerbated by, both internal [45] and external [50] tibial rotation. External tibial rotation, in particular, is a concern due to ACL impingement against the lateral wall of the intercondylar notch [50]. 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 [50].

Fig. 8.3 Frontal plane view of valgus knee position

Fig. 8.4 Frontal plane view of varus knee position

While the role of 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 [30]. As a result, the potential role of the gastrocnemius in injury prevention deserves consideration [30]. These data show that hip rotation and tibial rotation are likely to be important factors in ACL injuries, with knee external rotation in the transverse plane representing the issue of greatest concern. Figures 8.5 and 8.6 show a neutral and an internally rotated tibia, respectively. Figure 8.7 shows an externally rotated tibia, which may be the frontal plane condition that contributes the most to ACL injuries.

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 a quadriceps-induced anterior translation of the

Fig. 8.5 Transverse plane view of a relatively neutral tibia (knee)

Fig. 8.6 Transverse plane view of an internally rotated tibia (knee)

Fig. 8.7 Transverse plane view of an externally rotated tibia (knee)

tibia, are enough to rupture the ACL. Transverse plane biomechanics are also equivocal. It seems that femoral internal rotation (and thus tibia external rotation), as well as tibial internal rotation, may each play a part of the biomechanics of ACL injuries. However, the role of frontal plane biomechanics seems more certain. Knee valgus, potentially induced by eversion of the foot and adduction of the femur, dominance of the lateral compared to the medial aspects of the hamstring and quadriceps during noncontact conditions, and the addition of lateral exogenous forces during contact conditions, increases ACL injury risk. To the highest degree possible, 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 [52].

Critical Points

- Movements in each plane of motion are caused by external forces as well as muscle activation.
- Some muscle activation produces undesirable movements in each plane of motion, which stress the ACL.
- Lower extremity movements in the sagittal and transverse planes may be part of the etiology of ACL injuries, but the research is equivocal.
- Frontal plane biomechanics include ankle eversion, femur adduction, and knee valgus
- Frontal plane biomechanics issues of concern include the dominance of the lateral knee flexors and extensors which contribute to the 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 which resist undesirable movements.

Muscle Activation Patterns During Running

A number of studies have assessed muscle activation during gait, including running in barefoot and shod conditions [59, 60], on treadmills [3, 9, 13], over ground [42, 43, 59], on grass compared to tartan surfaces [60], and during various running speeds [13, 42, 43]. Some of these studies were conducted with the expressed purpose of assessing gender differences [2, 9, 11, 59], whereas others used both male and female subjects in the analysis without identifying gender differences as part of the purpose of the study [42, 43]. Some researchers examined muscle activation differences of subjects who were rehabilitated or underwent surgical reconstruction for ACL injuries [10]. 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, though the implications for ACL injury risk or neuromuscular protection remain equivocal.

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 [59], peroneus (fibularis) longus [2, 60], soleus [13], and the medial and lateral gastrocnemius [42, 43, 59]. 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 [13], or for activation of the lateral gastrocnemius and the tibialis anterior while sprinting over ground [43]. 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 [2] and less preactivation of the tibialis anterior [59].

After foot contact is made during running, gender differences in muscle activation are more pronounced. Studies show that gender differences exist 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 [59]. The tibialis anterior short time mean frequency EMG raised 20 ms earlier for women compared to men, potentially due to a shorter stance phase [59]. Finally, women, compared to men, had more tibialis anterior activation during the toe-off portion of the stance phase [59]. Activation of the tibialis anterior in the early and late stance phase of running is typical for uninjured individuals compared to those who had undergone ACL rehabilitation or surgical repair [10] 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, though the written description does not make clear the specific details of these differences [60]. However, others found clearer gender differences in the timing and magnitude of peroneus longus activation [2]. For example, 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 [2].

While much of the research focus has been on the gender differences in peroneus longus and tibialis anterior activation, researchers have also assessed gender differences in gastrocnemius activation. Some evidence suggests that the magnitude of gender differences is determined by running speed, such that women increase gastrocnemius activation more than men as sprinting speeds increase [42]. The specific characteristics of these differences in muscle activation have also been assessed by examining the frequency aspects of EMG. Results reveal gender 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 [59].

Activation of Muscles Commonly Associated with the Knee Joint

Gender differences in the activation of the muscles that cross the knee 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 "hamstrings" group including the biceps femoris, semitendinosus, and semimembranosus [32, 42, 43, 59], or the "quadriceps" group including the rectus femoris, vastus medialis, and vastus lateralis [9, 42, 43, 59, 60].

Some evidence suggests that there are no gender differences in prefoot contact muscle activity for specific hamstring or quadriceps group muscles such as the biceps femoris, rectus femoris, or vastus lateralis [43]. Nonetheless, other researchers have reported gender differences. For example, women compared to men have been shown to have higher precontact low-frequency hamstring activation during running [59]. Additionally, after foot contact, women have less hamstring activity during the stance phase of running [59]. The magnitude of hamstring activation that occurs during gait may be influenced by training. After 3–4 weeks of 10 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 [32]. 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 [32], 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 [59]. 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 beginning of the push-off phase of running [42]. Compared to men, women also had later onset and earlier decrease in vastus medialis activity [59]. Gender differences in vastus medialis activation appear to be manifested during both barefoot and shod conditions [60]. 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 [42] and on treadmills [9]. It is believed that this gender difference in vastus lateralis activation with increased treadmill running speed is possibly due to greater nonsagittal motion [9]. Similarly, women increase their vastus lateralis activation more than men with increasing sprinting speed while running over ground [42]. In addition to gender-specific responses to acute variables such as sprinting speed, gender differences are also affected by training. For example, peak vastus lateralis activation values were higher at midstance for women than men before training in one study. 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 [32].

Activation of Muscles Commonly Associated with the Hip Joint

Relatively little information can be gleaned regarding gender differences in the activation of muscles that cross the hip during running. One exception is the work of Mero and Komi that demonstrated no gender differences exist in prefoot contact activity for gluteus maximus [42, 43]. Others have found that, with increased speeds of treadmill running, women demonstrate a greater increase in gluteus maximus and medius muscle activations than men [9]. This response is thought to be due to greater nonsagittal plane motion noted in women [9].

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 but less activation of tibialis anterior [59] prior to foot contact during treadmill and over ground running, respectively. The tibialis anterior short time mean frequency EMG raised 20 ms earlier for women compared to men in one study, potentially due to a shorter stance phase [59]. Additionally, after foot contact, women have less hamstring activity during the stance phase of running [59]. Some evidence suggests that there are gender differences in fatigue resistance during running [6], even though women increase muscle activation to a greater degree than 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 [42] and on treadmills [9]. Some gender differences in muscle activation are thought to be related to body weight, connective tissue, dynamic segment alignment, and gender-specific movement behavior [60], potentially due to greater frontal and transverse plane movement [9]. Despite possible gender differences in movement patterns and muscle activation, little evidence shows that 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 performance as opposed to 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 activity during the stance phase of running.
- Some gender differences in muscle activation may be potentially due to greater frontal and transverse plane movement for women.
- Compared to jump landings and cutting, ACL injuries associated with running seem to be less common.

Muscle Activation Patterns During Cutting

Gender differences in muscle activation have been examined during cutting movements including side or side-step cutting [4, 26, 34, 35, 55], sprint and 45° cutting [18], and cross-cutting [34, 35]. 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 stimuli which required a quick reaction [3, 34, 35]. Many of these studies assessed the timing and magnitude of muscle activation prior to and after foot contact, since both the magnitude of activation and the timing of activation are believed to be important for knee joint stability and ACL injury prevention [30]. Collectively, these studies provide a background for understanding the gender differences in activation of muscles crossing the ankle, knee, and hip during cutting movements.

Activation of Muscles Commonly Associated with the Ankle Joint

Compared to men, women have greater lateral and medial gastrocnemius activity before ground contact and during the early stance phase of the side cut [35]. Furthermore, women have higher gastrocnemius activity, a medial-to-lateral gastrocnemius imbalance during unanticipated side cutting, and greater lateral gastrocnemius activity during unanticipated cross-cutting [34, 35]. Gender differences in gastrocnemius activation are present for younger subjects as well. Adolescent females demonstrate greater lateral gastrocnemius activity during precontact and the early stance phase of the cross-cut than adolescent males [35]. Thus, there are clear gender differences in activation of muscles crossing the ankle joint.

Activation of Muscles Commonly Associated with the Knee Joint

While some evidence suggests that there are no gender differences in quadriceps muscle activation [4] or lateral hamstring or medial hamstring activation [55] during side cutting, a number of studies demonstrate gender differences in both the timing and magnitude of activation of muscles that cross the knee joint during cutting.

Gender differences in the timing of muscle activation have been found during a variety of cutting maneuvers. Compared to men, women have longer rectus femoris and vastus lateralis activity after foot contact during a sprint and 45° cut [18] and an earlier and more rapid rise in rectus femoris activity prior to foot contact during cross-cutting [35].

Gender differences have also been reported in the magnitude of muscle activation during cutting. Women produce less hamstring activity prior to foot contact during side cutting than men [4] and lower hamstring-to-quadriceps ratios [26]. Gender differences in muscle activation have also been found after foot contact including lower medial hamstring activation during a side cut, lower lateral hamstring activation during a cross-cut [34], and less medial and lateral hamstring activation during a sprint and 45° cut [18]. These findings were true for adolescent [35], collegiate subjects [18], and athletes [26, 34].

In addition to lower levels of hamstring activation, women typically produce greater quadriceps activation during cutting than men. For example, in the first 20 % of the foot contact phase of cutting, women produce more total quadriceps activation [55]. Adolescent females have been shown to display more rectus femoris activation early in stance [35]. Women have a longer rectus femoris and vastus medialis burst after foot contact [18] and greater vastus medialis, vastus lateralis, and rectus femoris activity throughout the stance phase [34, 35]. Additionally, compared to men, women have greater vastus lateralis and quadriceps-to-hamstring ratios during the precontact and postcontact phases of side-step cutting movements [26]. These gender differences were found for subjects ranging from adolescents [35] to similarly trained Division I collegiate soccer athletes [26].

Activation of Muscles Commonly Associated with the Hip Joint

Although numerous researchers have investigated muscle activation during cutting, they did not examine muscles that cross the hip joint such as the gluteus maximus and gluteus medius [3, 4, 18, 34, 35, 55]. As a result, little evidence exists either for the presence or absence of gender differences of these muscles. One study that investigated this issue revealed that women, compared to men, demonstrate greater activation of their gluteus medius in the precontact phase of side-step cutting [26].

Summary

Compared to males, females have greater lateral and medial gastrocnemius activity prior to ground contact [35], higher gastrocnemius activity [34], and a medial-to-lateral gastrocnemius imbalance [34], 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 hamstrings-to-quadriceps ratios. Finally, 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 appear to activate the gastrocnemius more and are lateral gastrocnemius dominant during cutting.
- Women compared to men demonstrate earlier and longer quadriceps muscle activation upon foot contact.
- Women compared to men produce greater quadriceps activation during the pre- and postfoot contact phases of cutting.
- Women compared to men produce less hamstring activation in 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 prefoot contact phase of cutting.

Muscle Activation Patterns During Jumping and Landing

Numerous studies have assessed muscle activation during the pre- and post-foot contact phase of jump landings for the purpose of assessing gender differences and the etiology of ACL injuries. Jump landing conditions that have been studied include bilateral drop-jump landings from 15 cm [22], 24 cm [25], 30 cm [7, 22], 30.5 cm [61], 32 cm [40], 40 cm [49], 45 cm [22], and 45.8 cm [61]; 52-cm bilateral landings after a fatigue stimulus [24]; and drop-jump landings normalized to subject jump height [18]. Others have studied single-leg drop jumps from a 60-cm box [23], 100-cm forward jumps [23], 100-cm single forward hops [28, 47, 48], vertical stop jumps [8], and jumping at 50 % of maximum vertical jump capability [54]. Many of these types of jump landings have been implicated as part of the etiology of ACL injuries [30]. 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.

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 both single-leg and bilateral landings from 40-cm depth jumps [49].

Activation of Muscles Commonly Associated with the Knee Joint

Muscles affecting the knee joint have been studied by investigators seeking to assess gender differences in their activation during jump landings. These studies sought to evaluate the hamstring and quadriceps muscles by assessing the timing and magnitude of their activation during a variety of jump landings.

In some cases, no gender differences were found in the timing of activation. One study showed no differences in the onset of the burst of any of the hamstring muscles assessed prior to foot contact during jump landings [18]. Additionally, there were no differences in activation duration after foot contact for any of the hamstring or quadriceps muscles studied [18].

In addition to a lack of gender differences in timing of muscle activation, some studies were unable to find any gender differences in the magnitude of quadriceps muscle group activation during jump landings. For example, there was no significant difference in vastus medialis when jumping at 50 % of the subject's ability [54], or in rectus femoris in single-leg and bilateral conditions during 40-cm drop jumps [45, 49]. Similarly, no gender differences in vastus medialis, vastus lateralis, or rectus femoris activation were found in the precontact or postcontact phase of landing from drop jumps from heights that were equal to each subject's maximal countermovement jump height [18].

Similarly, gender differences in the magnitude of hamstrings activation during jump landings have not been substantiated in some studies. For example, no gender differences in activation of the lateral and medial hamstrings were found during the precontact phase [18] or postcontact phase of jump landings [45, 49, 54]. It is possible that fatigue may impair hamstring function, although gender differences during jump landing were not found after fatiguing protocols [24]. Finally, there were no gender differences reported in hamstring-to-quadriceps activation ratio during 24-cm drop jumps [25], in single-leg drop jumps from 30 cm in adolescent nonathletes, or during drop-jump landings from 32 cm in adolescent athletes [40]. Regardless of the type of jump studied, gender differences in hamstring-to-quadriceps activation ratio were not found in a variety of studies including those that assessed jumping at 50 % of subject capability [54]; during 24-cm drop jumps [25], 32-cm drop jumps [40], single- or two-leg landings from 40 cm [49], and drop jumps normalized to jumping ability [18]; or while in fatigued states [24].

While some studies failed to find gender difference in the timing of muscle activation, some evidence demonstrates that differences may exist during jump landings. During the precontact phase of the drop jump, women were found to activate their vastus lateralis [18, 24] and vastus medialis [18] earlier and lateral hamstrings later, than men [24]. Untrained adolescent females activated their rectus femoris later in the precontact phase of jumping landings than athletic boys and girls and their vastus medialis oblique later in the precontact phase than athletic girls [40].

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 during jump landings. For example, women have greater rectus femoris activation prior to contact [45, 61] and 12 % more activation than men for the collective average of the quadriceps muscles (vastus lateralis, vastus medialis, and rectus femoris) activation after contact during stop-jump landing [8].

Gender differences in hamstring activation during jump landings have also been found. Women demonstrate more hamstring activation before landing [8] but less lateral hamstring activation [18] or trending toward less [8] hamstring activation after foot contact on 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. However, in comparison, the activation of quadriceps muscles is higher which demonstrates that the hamstring muscle group activation did not increase to match the increased quadriceps muscle group activation during increasingly intense jump conditions [22].

Some evidence suggests that not only are there gender differences in hamstring and quadriceps activation levels and hamstring-to-quadriceps ratio but also in medial-to-lateral quadriceps ratios. One study showed that during the postcontact phase of foot strike on jump landings, women had less lateral hamstring activation than men [18]. However, more evidence suggests that women demonstrate a lower medial-to-lateral quadriceps ratio than men [44]. In fact, women seem to have lower activation of medial muscles of both the hamstring and quadriceps group. Thus, their vastus medialis and medial hamstrings are deficient compared to their vastus lateralis and lateral hamstrings, respectively [44, 48]. 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 [48]. 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 [45].

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 [7] and after foot contact during jump landings [7, 23, 24]. The absence of gender differences in gluteus maximus activation was present for recreationally trained individuals [7], as well as more athletic subjects such as Division I collegiate soccer players [23], and did not change when subjects were exposed to 120 repetitions of leg press exercise in an effort to induce fatigue [24]. Thus, men and women seemed 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 interesting to note that in some cases, statistically 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 postfoot contact phase of the drop jump [7]. Additionally, during 100-cm horizontal jumps with single-leg landings, gluteus medius activity was 2.26 times higher in men than women, which was also not statistically different [28]. In some cases, gluteus medius activation was found to be higher in males than females when assessed for a 200-ms period after landing, although no significant differences were found for other muscles assessed [23]. While gender differences were sometimes not found for the gluteus medius, Zazulak et al. [61] showed that women activated the gluteus maximus less than men during drop-jump landings from 30.5 to 45.8 cm.

Summary

Studies examining muscle activation during jumping have investigated a variety 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 [7, 8, 18, 24, 28, 44, 45, 47, 54], others used athletes [4, 23, 61] or adolescents [25, 40] as subjects. Some studies failed to show gender differences in muscle activation patterns for specific muscle groups [18, 24, 45, 49, 54]. However, differences in both the timing and the magnitude of activation have frequently been found [7, 8, 18, 21, 22, 24, 40, 44, 45, 49, 61]. 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 lateral dominant [48] at the knee joint in the frontal plane, as evidenced by lower medial-to-lateral hamstring and quadriceps activation than men during jump landing [44]. Compared to men, women also disproportionately increase quadriceps group activation compared to hamstring activation with increasing jump heights [22]. In some cases, women display less gluteus maximus activation than men [61]. Finally, some evidence shows that women also demonstrate less gluteus medius activation than men, though large mean differences were not statistically significant [28].

Critical Points

- A large number of studies have been conducted assessing gender differences in muscle activation during a variety of jump landings including bilateral and unilateral conditions and drop jumps from differing heights.
- Gender differences were not found for some studies or for specific muscles studied.
- The literature is mixed with respect to gender differences in the timing and magnitude of muscle activation during jump landings.
- Some evidence shows gender differences in muscle activation timing characterized by women demonstrating delayed onset of the hamstring and quadriceps muscles in the pre- and post foot-contact phase.
- For studies showing gender 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.

Summary

ACL injuries occur shortly after foot contact [58] 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 [51], at the same approximate time when the ACL ligament tension is the highest [58]. From the perspective of knee flexion during landing, the ACL ligament loading is greatest at 22.0° for men and 24.9° for women [36]. ACL loading decreases with increased knee flexion [58], but women demonstrate less hip and knee flexion than men during some tasks such as cutting [38].

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 ACL ligament rupture [37]. 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 has been questioned in a published review [5]. However, this source conducted the literature review in 2008 and included only two studies that evaluated muscle activation [5]. Now, it seems clear that women are quadriceps dominant and/or hamstring insufficient during some athletic movements such as cutting [18, 26, 34, 35, 55] and jump landings [8, 18, 22, 45, 61]. 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 [22]. Thus, increasing intensity of some form of exercise increases the quadriceps dominance of women compared to men [22].

Additionally, the role of the muscles such as the gastrocnemius may aid in stabilization in the sagittal plane, but has not been comprehensively studied. Muscles such as the gastrocnemius and others 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 [30] 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 deserves more consideration. Ultimately, mechanisms of ACL injury do not occur in only one plane (such as the sagittal plane) but are multiplanar.

Frontal Plane Mechanics

Gender differences in frontal plane mechanics are characterized by lateral femoral condyle lift-off and medial condyle compression resulting in frontal plane valgus [30]. These phenomena are more typical for women than men and produce ACL loading high enough to cause rupture, with higher loads found for women compared to men [39]. This medial-to-lateral imbalance is due in part to the fact that women have a lower medial hamstrings and medial quadriceps compared to lateral hamstring and lateral quadriceps ratios during jump landings [44, 48]. Women also have a medial-to-lateral gastrocnemius imbalance during cutting [34]. The result of this imbalance is the valgus knee condition, which is present for adolescents [21] and adults [38], and is exacerbated by the fact that women have greater ankle eversion [21, 33] and hip adduction [33, 38] 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 compared to 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 medialis 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 was not sufficient to identify them due to insufficient power and type II error [12]. As previously stated, muscles such as the gluteus maximus and medius are relatively unstudied for other movements such as cutting, so their contribution to frontal plane biomechanics remains uncertain.

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 tasks due to the role of these muscles in stabilizing knee joint rotation [31]. During cutting, females have higher gastrocnemius activity than men [34] and a medial-to-lateral gastrocnemius imbalance [34] that is characterized by greater lateral gastrocnemius activation during the precontact and early stance phase of the cross-cut [35] and higher lateral gastrocnemius activity [34]. 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 [31, 44]. 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 [31]. Numerous researchers have investigated muscle activation during cutting, but did not examine muscles that typically are 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.

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

Table 8.1 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 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 joint 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

statistically significant differences problematic [10]. 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 gender differences in the biomechanics of running, cutting, and landing. Table 8.1 represents the required muscle activation for reducing ACL injuries.

Exercises that optimally activate these muscles which 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 exercises such as the Russian curl, stiff leg deadlift, single-leg stiff leg deadlift, and good morning compared to other closed kinetic chain exercises such as the squat [16]. Closed kinetic chain exercises such as the deadlift produce more hamstring activation than other exercises characterized by hip and knee extension [17]. The deadlift, compared to other closed kinetic chain exercises such as the lunge, squat, and step-up, optimally activates the lateral hamstrings and medial hamstrings [19]. Unfortunately, the deadlift 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 MVIC [16]. The development of higher H:Q 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 [17]. Resistance training using exercises known to activate the hamstrings [16] was more effective than plyometric training at improving H:Q ratios during cutting and jump landings (data from the author's laboratory), even when using plyometric exercises with the greatest mean hamstring activation [15].

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 deadlift and squat [19]. Of these, the step-up produces the greatest mean EMG [19]. Variations of the step-up have been studied using 6 repetition maximum loads. The crossover step-up produces the greatest mean gluteus medius activation compared to other variations of this exercise [56]. In addition to the gluteus medius, some evidence shows gluteus maximus activation is greatest during the step-up, lunge, and deadlift, compared to the squat [19].

Muscles that cross the ankle joint, such as the gastrocnemius, may be affected by foot position during training. Medial gastrocnemius activation is enhanced with an externally rotated foot, whereas lateral gastrocnemius activation is increased with internal rotation of the foot [53] 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 adult 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.

References

1. Alentorn-Geli E, Myer GD, Silvers HJ et al (2009) Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. Knee Surg Sports Traumatol Arthrosc 17(8):859–879
2. Baur H, Hirschmuller A, Cassel M et al (2010) Gender-specific neuromuscular activity of the M. peroneus longus in healthy runners – a descriptive laboratory study. Clin Biomech (Bristol, Avon) 25(9):938–943
3. Beaulieu ML, Lamontagne M, Xu L (2008) Gender differences in time-frequency EMG analysis of unanticipated cutting maneuvers. Med Sci Sports Exerc 40(10):1795–1804
4. Bencke J, Zebis MK (2011) The influence of gender on neuromuscular pre-activity during side-cutting. J Electromyogr Kinesiol 21(2):371–375

5. Benjaminse A, Gokeler A, Fleisig GS et al (2011) What is the true evidence for gender-related differences during plant and cut maneuvers? A systematic review. Knee Surg Sports Traumatol Arthrosc 19(1): 42–54
6. Billaut F, Bishop D (2009) Muscle fatigue in males and females during multiple-sprint exercise. Sports Med 39(4):257–278
7. Carcia CR, Martin RL (2007) The influence of gender on gluteus medius activity during a drop jump. Phys Ther Sport 8:169–176
8. Chappell JD, Creighton RA, Giuliani C et al (2007) Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury. Am J Sports Med 35(2):235–241
9. Chumanov ES, Wall-Scheffler C, Heiderscheit BC (2008) Gender differences in walking and running on level and inclined surfaces. Clin Biomech (Bristol, Avon) 23(10):1260–1268
10. Ciccotti MG, Kerlan RK, Perry J et al (1994) An electromyographic analysis of the knee during functional activities. I. The normal profile. Am J Sports Med 22(5):645–650
11. Coh M, Dolenec A, Jost B (1999) Analysis of kinematic, kinetic, and electromyographic parameters of the sprinting stride of top female sprinters. Acta Kinesiologiae Universitatis Tartuensis 4:147–160
12. Cohen J (1992) A power primer. Psychol Bull 112(1):155–159
13. DeMont RG, Lephart SM (2004) Effect of sex on preactivation of the gastrocnemius and hamstring muscles. Br J Sports Med 38(2):120–124
14. Domire ZJ, Boros RL, Hashemi J (2011) An examination of possible quadriceps force at the time of anterior cruciate ligament injury during landing: a simulation study. J Biomech 44(8):1630–1632
15. Ebben WP, Simenz C, Jensen RL (2008) Evaluation of plyometric intensity using electromyography. J Strength Cond Res 22(3):861–868
16. Ebben WP (2009) Hamstring activation during lower body resistance training exercises. Int J Sports Physiol Perform 4(1):84–96
17. Ebben WP, Feldmann CR, Dayne A et al (2009) Muscle activation during lower body resistance training. Int J Sports Med 30(1):1–8
18. Ebben WP, Fauth ML, Petushek EJ et al (2010) Gender-based analysis of hamstring and quadriceps muscle activation during jump landings and cutting. J Strength Cond Res 24(2):408–415
19. Fauth ML, Garceau LR, Lutsch BN et al (2010) Hamstring, quadriceps and gluteal muscle activation during resistance training exercises. Paper presented at the 28th conference on biomechanics in sports, Marquette, 19–23 July 2010
20. Fauth ML, Petushek EJ, Feldmann CR et al (2010) Reliability of surface electromyography during maximal voluntary isometric contractions, jump landings, and cutting. J Strength Cond Res 24(4):1131–1137
21. Ford KR, Myer GD, Toms HE et al (2005) Gender differences in the kinematics of unanticipated cutting in young athletes. Med Sci Sports Exerc 37(1):124–129
22. Ford KR, Myer GD, Schmitt LC et al (2011) Preferential quadriceps activation in female athletes with incremental increases in landing intensity. J Appl Biomech 27(3):215–222
23. Garrison JC, Hart JM, Palmieri-Smith RM et al (2005) Lower extremity EMG in male and female college soccer players during single-leg landing. J Sport Rehabil 14(1):48–57
24. Gehring D, Melnyk M, Gollhofer A (2009) Gender and fatigue have influence on knee joint control strategies during landing. Clin Biomech (Bristol, Avon) 24(1):82–87
25. Hamstra-Wright KL, Swanik CB, Sitler MR et al (2006) Gender comparisons of dynamic restraint and motor skill in children. Clin J Sport Med 16(1):56–62
26. Hanson AM, Padua DA, Troy Blackburn J et al (2008) Muscle activation during side-step cutting maneuvers in male and female soccer athletes. J Athl Train 43(2):133–143
27. Harmon KG, Ireland ML (2000) Gender differences in noncontact anterior cruciate ligament injuries. Clin Sports Med 19(2):287–302
28. Hart JM, Garrison JC, Kerrigan DC et al (2007) Gender differences in gluteus medius muscle activity exist in soccer players performing a forward jump. Res Sports Med 15(2):147–155
29. Hewett TE, Stroupe AL, Nance TA et al (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24(6):765–773
30. Hewett TE, Zazulak BT, Myer GD et al (2005) A review of electromyographic activation levels, timing differences, and increased anterior cruciate ligament injury incidence in female athletes. Br J Sports Med 39(6):347–350
31. Houck J (2003) Muscle activation patterns of selected lower extremity muscles during stepping and cutting tasks. J Electromyogr Kinesiol 13(6):545–554
32. Hurd WJ, Chmielewski TL, Snyder-Mackler L (2006) Perturbation-enhanced neuromuscular training alters muscle activity in female athletes. Knee Surg Sports Traumatol Arthrosc 14(1):60–69
33. Joseph MF, Rahl M, Sheehan J et al (2011) Timing of lower extremity frontal plane motion differs between female and male athletes during a landing task. Am J Sports Med 39(7):1517–1521
34. Landry SC, McKean KA, Hubley-Kozey CL et al (2007) Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. Am J Sports Med 35(11):1888–1900
35. Landry SC, McKean KA, Hubley-Kozey CL et al (2009) Gender differences exist in neuromuscular control patterns during the pre-contact and early stance phase of an unanticipated side-cut and cross-cut maneuver in 15-18 years old adolescent soccer players. J Electromyogr Kinesiol 19(5):e370–e379

36. Lin CF, Gross M, Ji C et al (2009) A stochastic biomechanical model for risk and risk factors of non-contact anterior cruciate ligament injuries. J Biomech 42(4):418–423
37. McLean SG, Huang X, Su A et al (2004) Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. Clin Biomech (Bristol, Avon) 19(8):828–838
38. McLean SG, Lipfert SW, van den Bogert AJ (2004) Effect of gender and defensive opponent on the biomechanics of sidestep cutting. Med Sci Sports Exerc 36(6):1008–1016
39. McLean SG, Walker KB, van den Bogert AJ (2005) Effect of gender on lower extremity kinematics during rapid direction changes: an integrated analysis of three sports movements. J Sci Med Sport 8(4):411–422
40. Medina JM, Valovich McLeod TC, Howell SK et al (2008) Timing of neuromuscular activation of the quadriceps and hamstrings prior to landing in high school male athletes, female athletes, and female non-athletes. J Electromyogr Kinesiol 18(4):591–597
41. Melnyk M, Gollhofer A (2007) Submaximal fatigue of the hamstrings impairs specific reflex components and knee stability. Knee Surg Sports Traumatol Arthrosc 15(5):525–532
42. Mero A, Komi PV (1986) Force-, EMG-, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. Eur J Appl Physiol Occup Physiol 55(5):553–561
43. Mero A, Komi PV (1987) Electromyographic activity in sprinting at speeds ranging from sub-maximal to supra-maximal. Med Sci Sports Exerc 19(3): 266–274
44. Myer GD, Ford KR, Hewett TE (2005) The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. J Electromyogr Kinesiol 15(2): 181–189
45. Nagano Y, Ida H, Akai M et al (2007) Gender differences in knee kinematics and muscle activity during single limb drop landing. Knee 14(3):218–223
46. Neumann D (2002) Kinesiology of the musculoskeletal system. Foundations for physical rehabilitation. Mosby, St. Louis
47. Palmieri-Smith RM, Wojtys EM, Ashton-Miller JA (2008) Association between preparatory muscle activation and peak valgus knee angle. J Electromyogr Kinesiol 18(6):973–979
48. Palmieri-Smith RM, McLean SG, Ashton-Miller JA et al (2009) Association of quadriceps and hamstrings cocontraction patterns with knee joint loading. J Athl Train 44(3):256–263
49. Pappas E, Hagins M, Sheikhzadeh A et al (2007) Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. Clin J Sport Med 17(4):263–268
50. Park HS, Wilson NA, Zhang LQ (2008) Gender differences in passive knee biomechanical properties in tibial rotation. J Orthop Res 26(7):937–944
51. Pollard CD, Heiderscheit BC, van Emmerik RE et al (2005) Gender differences in lower extremity coupling variability during an unanticipated cutting maneuver. J Appl Biomech 21(2):143–152
52. Quatman CE, Quatman-Yates CC, Hewett TE (2010) A 'plane' explanation of anterior cruciate ligament injury mechanisms: a systematic review. Sports Med 40(9):729–746
53. Riemann BL, Limbaugh GK, Eitner JD et al (2011) Medial and lateral gastrocnemius activation differences during heel-raise exercise with three different foot positions. J Strength Cond Res 25(3):634–639
54. Russell PJ, Croce RV, Swartz EE et al (2007) Knee-muscle activation during landings: developmental and gender comparisons. Med Sci Sports Exerc 39(1): 159–170
55. Sigward SM, Powers CM (2006) The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. Clin Biomech (Bristol, Avon) 21(1):41–48
56. Simenz CJ, Garceau LR, Lutsch BN et al (2012) Electromyographical analysis of lower extremity muscle activation during variations of the loaded step up exercise. J Strength Cond Res. Epub ahead of print Jan. 13, 2012. DOI: 10.1519/JSC.0b013e3182472fad
57. Smoliga JM, Myers JB, Redfern MS et al (2010) Reliability and precision of EMG in leg, torso, and arm muscles during running. J Electromyogr Kinesiol 20(1):e1–e9
58. Taylor KA, Terry ME, Utturkar GM et al (2011) Measurement of in vivo anterior cruciate ligament strain during dynamic jump landing. J Biomech 44(3): 365–371
59. von Tscharner V, Goepfert B (2003) Gender dependent EMGs of runners resolved by time/frequency and principal pattern analysis. J Electromyogr Kinesiol 13(3):253–272
60. Wissemann I, Potthast W Bruggemann G-P Changes in EMG signals while running on different surfaces. In: Schwameder H, Strutzenberger G, Fastenbauer V et al (eds) 24 international symposium on biomechanics in sport, Salzburg, 14–18 July 2006, pp 522–526
61. Zazulak BT, Ponce PL, Straub SJ et al (2005) Gender comparison of hip muscle activity during single-leg landing. J Orthop Sports Phys Ther 35(5):292–299

Proximal Risk Factors for ACL Injury: Role of Core Stability

9

Ajit M.W. Chaudhari, Steve T. Jamison, and Thomas M. Best

Contents

A.M.W. Chaudhari, Ph.D. (✉)
Department of Orthopaedics, Sports Health & Performance Institute, Ohio State University Sports Medicine Center,
2050 Kenny Rd, Suite 3100, Columbus, OH 43221, USA
e-mail: chaudhari.2@osu.edu

S.T. Jamison, Ph.D.
Department of Orthopaedics, Ohio State University Sports Medicine Center,
2050 Kenny Rd, Suite 3100, Columbus, OH 43221, USA
e-mail: stevetjamison@gmail.com

T.M. Best, M.D., Ph.D.
Department of Family Medicine, Sports Health & Performance Institute, Ohio State University Sports Medicine Center,
2050 Kenny Rd, Suite 3100, Columbus, OH 43221, USA
e-mail: tom.best@osumc.edu

Introduction

Core stability is a popular term in both the scientific literature and 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 [28, 43]. However, the term itself is vague and used in various methods 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 and core stability must first be defined.

Core Defined

The extent of the core region of the body itself has not been defined consistently across the literature.[1] 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

[1] The published literature contains two definitions of the musculoskeletal "core" of the body. The classic description includes all of the muscles of the trunk and pelvis required for stability of the spine and pelvis during activities. The second definition includes all trunk musculature, along with the hip muscles, required for stabilization of the pelvis and trunk during activities. In this chapter, the first definition of core is used by the authors.

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_9, © Springer-Verlag Berlin Heidelberg 2012

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, the authors define the core as the region of the body bounded by the pelvis and diaphragm which includes the muscles of the abdomen and lower back. By this definition, the muscles of the core are responsible for the position and movement of the trunk.

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" [35]. 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" [55]. 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 [54]. 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 [11], 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 sections "Video Observations of Core Motion During ACL Injury Events" and "Biomechanical Evidence Linking the Core to Knee Loading: Cross-Sectional Studies" for further discussion). Core stability may also contribute to athletic performance by providing "proximal stability for distal mobility" [28]. Hodges and Richardson [23] demonstrated that core muscle activation precedes activation of muscles responsible for moving the lower extremities. 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 a recent study of professional baseball pitchers by Chaudhari et al. [6], which showed that lumbopelvic control was associated with pitching performance. Pitchers with better control of the lumbopelvic region pitched significantly more innings and had significantly fewer walks, plus hits per inning pitched, over one season. 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.

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 [18] and Presidential Physical Fitness Test [50] quantify how many times a subject can perform a sit-up in a given amount of time. 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 an individual 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. 9.1) [33, 36]. In the 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 1 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). In this test (Fig. 9.2), 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 [36, 48]. 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 section "Introduction," 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 above-mentioned 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 [7, 8, 32]. These repetitive high spinal compression loads could over time lead to lumbar injuries such as low back pain, a ruptured vertebral disc, or spondylolisthesis [4, 16, 39]. 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 [53].

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

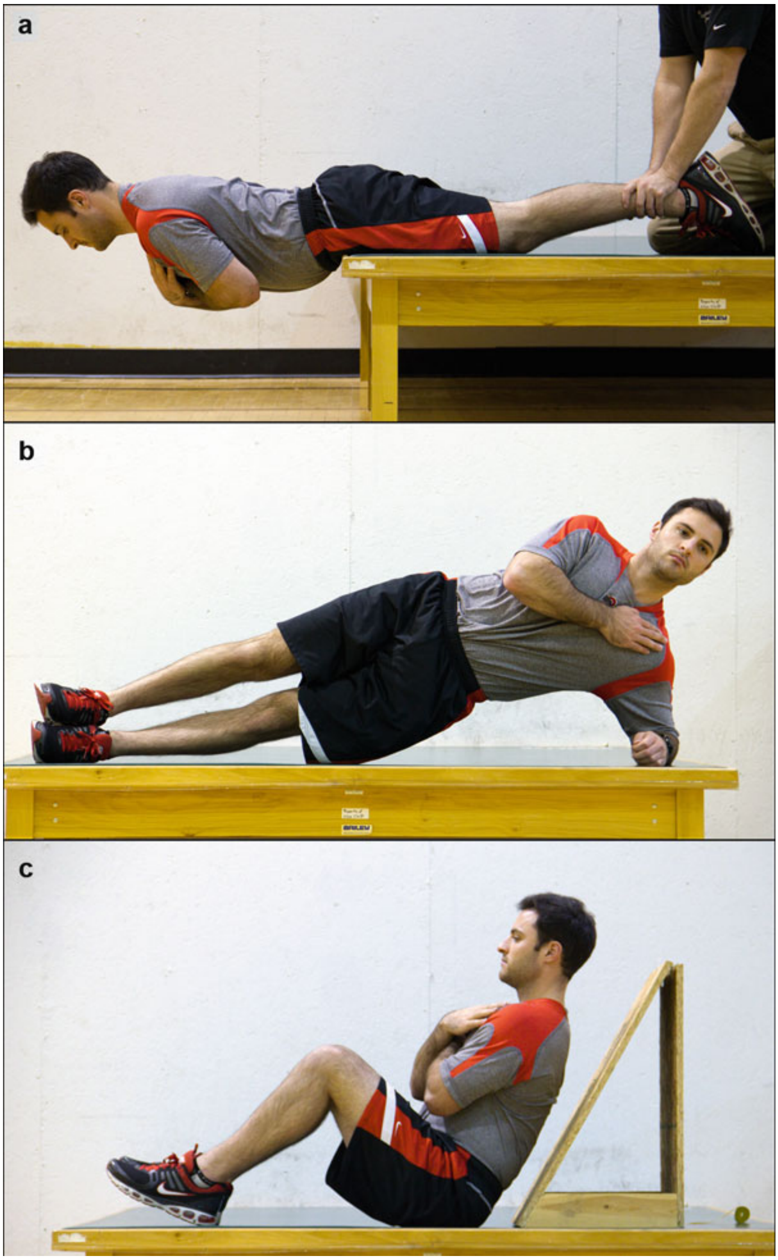


Fig. 9.1 Prone-plank (**a**), side-bridge (**b**), and flexor endurance (**c**) tests used to assess trunk endurance

side-plank, and flexor endurance tests [1, 15, 34], although 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 [25, 34, 51]. 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 [1, 42]. 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 a stable, fixed trunk [15].

Fig. 9.2 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

Several successful ACL injury prevention programs have included components of core-stability training [13, 17, 19, 30, 38, 41, 47]. However, it remains controversial whether improving core stability is a necessary component to reduce lower extremity injury risk, and 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 [21] highlighted two studies that incorporated some form of focused core exercises into their training programs; one used abdominal curls [19], while the other used perturbations to the trunk during standing on an unstable surface [38]. While a reduced incidence of ACL injuries was observed with each of 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. One study that incorporated crunches on a BOSU® exercise ball demonstrated a reduction in knee loading patterns implicated in ACL injury risk [37], but again the inclusion of any and all exercises that may be helpful precludes the determination of whether the addition of the core-focused exercises were important factors in the observed changes in knee kinematics.

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 is unknown.

Prospective Evidence Linking the Core to ACL Injuries

Three prospective studies investigated the link between aspects of core stability and ACL injuries. The first, conducted by Leetun et al. [29], 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. [55, 56] examined core stability as defined in section "Introduction." These studies highlighted a potential connection between core stability and female ACL injuries. A total of 140 female and 137 male varsity collegiate 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 studies, Zazulak et al. [55] quantified core proprioception using an apparatus originally designed by Taimela et al. [49] to produce passive motion of the lumbar spine in the transverse (horizontal) plane (Fig. 9.3). In

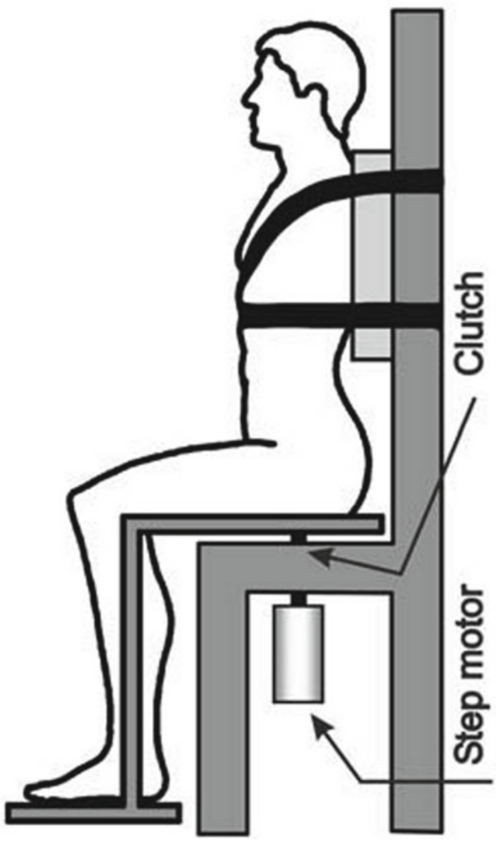


Fig. 9.3 Apparatus used by Zazulak et al. [55] to test core proprioception. The stepper motor rotates the seat 20°, holds for 3 s, and then is released using the clutch. Subjects rotate themselves back to what they perceive is the original, neutral position. The error between the perceived and actual positions is measured (Reproduced from Zazulak et al. [55]; with permission from SAGE Publications, Inc.)

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.

In the second study, Zazulak et al. [56] quantified isolated trunk control following sudden unloading in three directions (flexion, extension, and lateral bending; Fig. 9.4). 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 [55, 56], of the 277 (140 female) athletes that participated, 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 [55] indicated that women who later experienced knee and ligament/meniscus injuries had significantly greater repositioning errors than uninjured females ($P = .006$ and $P = .007$, respectively). Further, the authors found that for every degree of increased error, a 2.9-fold increase in the odds ratio of knee injury ($P = .005$) and a 3.3-fold increase in the odds ratio of ligament/meniscus injury ($P = .007$) were observed. No significant difference was observed between repositioning error of ACL injured and uninjured females, but the sample size (only four ACL injuries) was too small to draw definitive conclusions.

Results from the trunk control experiment [56] indicated that ligament-injured female athletes demonstrated greater maximum lateral displacements than uninjured female athletes ($P = .005$). When the results were collapsed across gender, maximum lateral displacement was significantly greater in all three injury classifications, including ACL injuries.

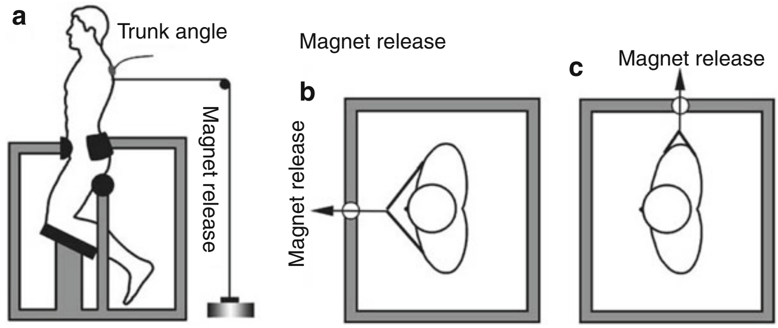


Fig. 9.4 A subject positioned in a multidirectional, sudden force release apparatus used by Zazulak et al. [56] and Jamison et al. [24, 25] to quantify trunk control. Subjects pulled in trunk flexion (**a**), extension (**b**), and lateral bending (**c**) against the cable with a prescribed force. Resisted force was suddenly released by deactivating the magnet and the subsequent trunk angular displacement was recorded (Reproduced from Zazulak et al. [56]; with permission from SAGE Publications, Inc.)

Results from these two studies suggest a role for core proprioception and trunk control, both contributing factors to core stability, in knee and ligamentous injury risk for females. The trunk control experiment also suggested an association when males and females were analyzed together between poorer trunk control and ACL injuries. Both 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 injury to any of the cruciate or collateral knee ligaments in female athletes.
- Decreased lateral trunk control has been associated with increased ACL injury risk in male and female varsity athletes.
- It remains unknown whether trunk control and proprioception cause ACL injury risk to increase or whether the association is merely coincidental.

Video Observations of Core Motion During ACL Injury Events

Most clinicians and researchers have observed an ACL injury at some point in time, either live or on video. It is impossible to know exactly when the injury occurs 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 motion of the core during injury events versus noninjury events.

Hewett et al. [22] 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 (11.1 ± 2° and −5.5 ± 9.5°, respectively, $P = .04$) and trended to greater trunk lean when compared to female controls (11.1 ± 2° and 4.2 ± 9.6°, respectively, $P = .29$).

Sheehan et al. [44] 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. [22]. 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. Significant differences were reported between injured and uninjured athletes in both trunk angle (4 ± 14° and 16 ± 13°, respectively, $P = .016$) and COM_BOS (1.5 ± 0.5 and 0.7 ± 0.7, respectively, $P < .001$), with the injured athletes having more upright posture and stretching the foot further in front of the center of mass.

The results of these studies must be considered in light of the limitations inherent to 2 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 described in section "Introduction" 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 provides 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.

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

As detailed in section "Prospective Evidence Linking the Core to ACL Injuries," most prospective research on core stability and ACL injury has focused on empirically identifying associations between core-stability measurements and ACL injury incidence. Studies such as these are critical to establish the extent of the injury problem, which is commonly accepted as the first step in preventing sports injuries [52]. 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 [22, 44], but due to the limitations of 2-dimensional video analysis, they serve best as a motivation for developing hypotheses that can be tested more rigorously with more sophisticated techniques. Along these lines, recent work using motion analysis and computer simulation have begun to explore the direct biomechanical connection between core stability and knee loading in greater detail.

Several recent cross-sectional studies have linked positioning of the upper body to knee-loading parameters which have been identified as risk factors for ACL injury, as described in Part 3. In particular, these studies examined peak external knee abduction moment (pEKAbM) as the knee-loading outcome of greatest interest during side-step cutting maneuvers, which are known to be high risk for ACL injury in field and court sports [3]. 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 in a prospective study in a population of female adolescent athletes [20]. Increasing knee abduction moments have also been associated with increased strain (elongation) of the ACL in both cadaver knees [14, 31] and computer simulations [45, 46].

Chaudhari et al. [5] in 2005 used markered-motion capture techniques and inverse dynamics to estimate the pEKAbM of 11 subjects (6 women, 5 men; mean age 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 in which 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 % ($P = .03$). When subjects held the lacrosse stick with both hands, the pEKAbM increased 60 % ($P = .03$).

Dempsey et al. [9] in 2007 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 ($P < .05$). Trunk twist resulted in 53 % higher peak tibial internal rotation moment (pTIRM) than the natural condition ($P < .05$). 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 [46] and force [27].

In another study using markered-motion capture and inverse dynamics to estimate knee moments, Jamison et al. [26] 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 [2]. In addition to calculating pEKAbM and pTIRM, outside tilt of the trunk (lateral angle away from direction of the cut) was calculated. Using multiple regression analysis to examine the relationship between moments and outside tilt as continuous variables within each individual, this study observed that pEKAbM was positively associated with outside tilt ($P = .002$), while pTIRM was negatively associated with outside tilt ($P = .021$). A positive association between torso tilt 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 outside tilt and pTIRM suggests that as outside tilt 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 trunk outside tilt on pEKAbM would be expected to increase the risk of ACL injury through an excessive valgus moment mechanism.

Donnelly et al. [12] applied computer simulation techniques to baseline data from markered-motion analysis in 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 and a scaled generic model were 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 9 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 [22], upright posture [44], and a more posterior center of mass relative to the foot [44].

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 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. Therefore, both Chaudhari et al. [5, 45] and Jamison et al. [26] advocate for future studies 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 effective 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 are needed to better understand the connection between the core and ACL injury.

The Core-ACL Connection: Causation or Just Correlation?

Although the evidence from cross-sectional, epidemiological, and interventional studies presented above (sections "Traditional Core Assessments and Training," "Prospective Evidence Linking the Core to ACL Injuries," "Video Observations of Core Motion During ACL Injury Events," and "Biomechanical Evidence Linking the Core to Knee Loading: Cross-Sectional Studies") 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 lacked the systematic approach necessary to determine if the core-directed exercises were 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 [40] 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. 9.5). 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 were filmed during three soccer training sessions to assess their movement patterns. Over these 27 h 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 [25] analyzed the effectiveness of two different 6-week training programs (whole-body resistance program and trunk stabilization program).

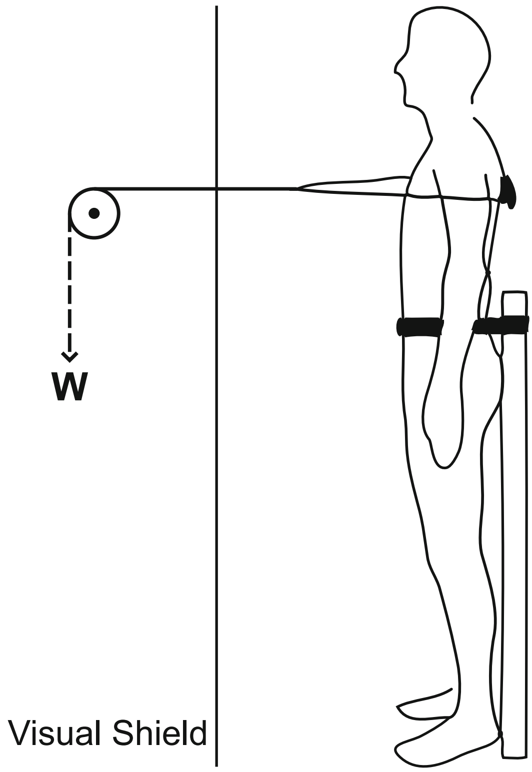


Fig. 9.5 Setup for generating a sudden forward pull to the upper part of the subject's trunk used by Pedersen et al. [40] to quantify trunk control. A cable is fastened to a rigid bar at the back by means of a harness attached to the upper part of the trunk. At a random time, an electromagnet is used 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. [40])

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 during an unanticipated 45° cut (section "Video Observations of Core Motion During ACL Injury Events") and displacement after a sudden force release (section "Prospective Evidence Linking the Core to ACL Injuries") were assessed pre- and posttesting for 22 men who completed the training programs (11 per intervention group). Athletes who participated in the whole-body resistance training program significantly worsened their knee loading (pEKAbM during the cut) and 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. However, the study was underpowered to test the ability of the programs to maintain these variables. 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 turned 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 (section "Introduction"), though this intriguing observation deserves further study.

A third study by Dempsey et al. [10] 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 were estimated during a 45° unanticipated side-step cut before and after the task-specific training. Significant reductions in pEKAbM ($P = .034$), lateral trunk lean ($P = .005$), and lateral reaching of the plant foot ($P = .039$) 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 [40]. Running and static trunk stabilization exercises do not appear to improve trunk control, although they may assist in maintaining control [25, 40]. Eliminating core-directed exercises in whole-body resistance training appears to negatively influence trunk control and knee loading [25]. 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 [40].

While these studies provide modest insight into the best ways to train the core and the possible 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 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.

Acknowledgment The authors would like to thank Steve McConoughey, Ph.D. for his editorial assistance with this manuscript.

References

1. Akuthota V, Nadler SF (2004) Core strengthening. Arch Phys Med Rehabil 85(3 Suppl 1):S86–S92
2. Besier TF, Lloyd DG, Ackland TR et al (2001) Anticipatory effects on knee joint loading during running and cutting maneuvers. Med Sci Sports Exerc 33(7):1176–1181
3. Boden BP, Dean GS, Feagin JA Jr et al (2000) Mechanisms of anterior cruciate ligament injury. Orthopedics 23(6):573–578
4. Callaghan JP, McGill SM (2001) Intervertebral disc herniation: studies on a porcine model exposed to highly repetitive flexion/extension motion with compressive force. Clin Biomech (Bristol, Avon) 16(1):28–37
5. Chaudhari AM, Hearn BK, Andriacchi TP (2005) Sport-dependent variations in arm position during single-limb landing influence knee loading: implications for anterior cruciate ligament injury. Am J Sports Med 33(6):824–830
6. Chaudhari AM, McKenzie CS, Borchers JR et al (2011) Lumbopelvic control and pitching performance of professional baseball pitchers. J Strength Cond Res 25(8):2127–2132
7. Childs JD, Teyhen DS, Benedict TM et al (2009) Effects of sit-up training versus core stabilization exercises on sit-up performance. Med Sci Sports Exerc 41(11):2072–2083
8. Childs JD, Teyhen DS, Casey PR et al (2010) Effects of traditional sit-up training versus core stabilization exercises on short-term musculoskeletal injuries in US Army soldiers: a cluster randomized trial. Phys Ther 90(10):1404–1412
9. Dempsey AR, Lloyd DG, Elliott BC et al (2007) The effect of technique change on knee loads during sidestep cutting. Med Sci Sports Exerc 39(10):1765–1773
10. Dempsey AR, Lloyd DG, Elliott BC et al (2009) Changing sidestep cutting technique reduces knee valgus loading. Am J Sports Med 37(11):2194–2200
11. Dempster WT, Gaughran RL (1967) Properties of body segments based on size and weight. Am J Anat 20(1):33–54
12. Donnelly CJ, Lloyd DG, Elliott BC et al (2012) Optimizing whole-body kinematics to minimize valgus knee loading during sidestepping: implications for ACL injury risk. J Biomech 45(8):1491–1497
13. Emery CA, Rose MS, McAllister JR et al (2007) A prevention strategy to reduce the incidence of injury in high school basketball: a cluster randomized controlled trial. Clin J Sport Med 17(1):17–24
14. Fleming BC, Renstrom PA, Beynnon BD et al (2001) The effect of weightbearing and external loading on anterior cruciate ligament strain. J Biomech 34(2):163–170
15. Fredericson M, Moore T (2005) Muscular balance, core stability, and injury prevention for middle- and long-distance runners. Phys Med Rehabil Clin N Am 16(3):669–689
16. Gallagher S, Marras WS, Litsky AS et al (2005) Torso flexion loads and the fatigue failure of human lumbosacral motion segments. Spine (Phila Pa 1976) 30(20):2265–2273
17. Gilchrist J, Mandelbaum BR, Melancon H et al (2008) A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. Am J Sports Med 36(8):1476–1483
18. Hemmerly-Brown A (2011) Soldiers try new PT test at Benning. United States Army. http://www.army.mil/article/56445/. Accessed 7 Feb 2012
19. Hewett TE, Lindenfeld TN, Riccobene JV et al (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27(6):699–706
20. Hewett TE, Myer GD, Ford KR et al (2005) Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med 33(4):492–501
21. Hewett TE, Ford KR, Myer GD (2006) Anterior cruciate ligament injuries in female athletes: part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. Am J Sports Med 34(3):490–498
22. Hewett TE, Torg JS, Boden BP (2009) Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral

trunk and knee abduction motion are combined components of the injury mechanism. Br J Sports Med 43(6):417–422
23. Hodges PW, Richardson CA (1997) Contraction of the abdominal muscles associated with movement of the lower limb. Phys Ther 77(2):132–142; discussion 142–134
24. Jamison ST, Chaudhari AM (2010) Influence of trunk neuromuscular control on run-to-cut maneuver: a risk factor for ACL rupture. In: 56th annual meeting of the orthopaedic research society. AAOS, New Orleans, p 1892
25. Jamison ST, McNeilan RJ, Young GS et al. (2012) RCT of the effects of a trunk stabilization program on trunk control and knee loading. Med Sci Sports Exerc http://www.ncbi.nlm.nih.gov/pubmed/22525777 Med Sci Sports Exerc. 2012 Oct; 44(10):1924–1934
26. Jamison ST, Pan X, Chaudhari AM (2012) Knee moments during run-to-cut maneuvers are associated with lateral trunk positioning. J Biomech 45(11): 1881–1885
27. Kanamori A, Zeminski J, Rudy TW et al (2002) The effect of axial tibial torque on the function of the anterior cruciate ligament: a biomechanical study of a simulated pivot shift test. Arthroscopy 18(4): 394–398
28. Kibler WB, Press J, Sciascia A (2006) The role of core stability in athletic function. Sports Med 36(3):189–198
29. Leetun DT, Ireland ML, Willson JD et al (2004) Core stability measures as risk factors for lower extremity injury in athletes. Med Sci Sports Exerc 36(6): 926–934
30. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010
31. Markolf KL, Burchfield DM, Shapiro MM et al (1995) Combined knee loading states that generate high anterior cruciate ligament forces. J Orthop Res 13(6):930–935
32. McGill SM (1995) The mechanics of torso flexion: situps and standing dynamic flexion manoeuvres. Clin Biomech (Bristol, Avon) 10(4):184–192
33. McGill SM, Childs A, Liebenson C (1999) Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. Arch Phys Med Rehabil 80(8):941–944
34. McGill SM (2009) Ultimate back fitness and performance. Backfitpro, Inc., Waterloo
35. Merriam-Webster (2012) Stability. Encyclopaedia Britannica. http://www.merriam-webster.com/dictionary/stability. Accessed 7 Feb 2012
36. Mills JD, Taunton JE, Mills WA (2005) The effect of a 10-week training regimen on lumbo-pelvic stability and athletic performance in female athletes: a randomized-controlled trial. Phys Ther Sport 6(2):60–66
37. Myer GD, Ford KR, Palumbo JP et al (2005) Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. J Strength Cond Res 19(1):51–60
38. Myklebust G, Engebretsen L, Braekken IH et al (2003) Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. Clin J Sport Med 13(2):71–78
39. Oxland TR, Panjabi MM (1992) The onset and progression of spinal injury: a demonstration of neutral zone sensitivity. J Biomech 25(10):1165–1172
40. Pedersen MT, Randers MB, Skotte JH et al (2009) Recreational soccer can improve the reflex response to sudden trunk loading among untrained women. J Strength Cond Res 23(9):2621–2626
41. Petersen W, Braun C, Bock W et al (2005) A controlled prospective case control study of a prevention training program in female team handball players: the German experience. Arch Orthop Trauma Surg 125(9): 614–621
42. Sahrmann S (2002) Diagnosis and treatment of movement impairment syndromes. Mosby, Philadelphia
43. Schuler L (2011) The six-pack fast track. Men's health. Rodale, Inc., Emmaus
44. Sheehan FT, Sipprell WH 3rd, Boden BP (2012) Dynamic sagittal plane trunk control during anterior cruciate ligament injury. Am J Sports Med 40(5): 1068–1074
45. Shin CS, Chaudhari AM, Andriacchi TP (2009) The effect of isolated valgus moments on ACL strain during single-leg landing: a simulation study. J Biomech 42(3):280–285
46. Shin CS, Chaudhari AM, Andriacchi TP (2011) Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. Med Sci Sports Exerc 43(8):1484–1491
47. Soligard T, Myklebust G, Steffen K et al (2008) Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. BMJ 337:a2469
48. Stanton R, Reaburn PR, Humphries B (2004) The effect of short-term Swiss ball training on core stability and running economy. J Strength Cond Res 18(3):522–528
49. Taimela S, Kankaanpaa M, Luoto S (1999) The effect of lumbar fatigue on the ability to sense a change in lumbar position. A controlled study. Spine (Phila Pa 1976) 24(13):1322–1327
50. The President's Council on Fitness SN (2012) Curl-ups. The President's Challenge. https://www.presidentschallenge.org/challenge/physical/activities/curl-ups.shtml. Accessed 8 Feb 2012
51. Tse MA, McManus AM, Masters RS (2005) Development and validation of a core endurance intervention program: implications for performance in college-age rowers. J Strength Cond Res 19(3):547–552

52. van Mechelen W (1992) Running injuries. A review of the epidemiological literature. Sports Med 14(5): 320–335
53. Whiting WC, Sugg S, Coleman A et al (1999) Muscle activity during sit-ups using abdominal exercise devices. J Strength Cond Res 13(4):339–345
54. Willson JD, Dougherty CP, Ireland ML et al (2005) Core stability and its relationship to lower extremity function and injury. J Am Acad Orthop Surg 13(5):316–325
55. Zazulak BT, Hewett TE, Reeves NP et al (2007) The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. Am J Sports Med 35(3):368–373
56. Zazulak BT, Hewett TE, Reeves NP et al (2007) Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. Am J Sports Med 35(7): 1123–1130

Proximal Risk Factors for ACL Injury: Role of the Hip

10

Susan M. Sigward and Christine D. Pollard

Contents

S.M. Sigward, Ph.D., P.T., A.T.C. (✉)
Division of Biokinesiology and Physical Therapy,
University of Southern California,
1540 E. Alcazar Street, CHP-155,
Los Angeles, CA 90089, USA
e-mail: sigward@usc.edu

C.D. Pollard, Ph.D., P.T.
Department of Nutrition and Exercise Science,
Oregon State University-Cascades,
2600 NW College Way, Cascades Hall,
Bend, OR 97701, USA
e-mail: christine.pollard@osucascades.edu

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 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.

Anatomical Considerations of Hip Joint

The hip joint is comprised of the articulation between the proximal femur and pelvis. 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

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_10, © Springer-Verlag Berlin Heidelberg 2012

hip abductor (gluteus medius [GMED]) are considered the most important antigravity muscles acting at the hip due to their location and force-generating capacity [48]. In addition, 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 [48]. 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 gluteus maximus has a large capacity for external rotation at smaller degrees of hip flexion. As the hip flexes, the moment arm for external rotation decreases reducing its force generating capacity for external rotation [10]. 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 mass, 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.

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 musculature. The knee joint affords considerable motion in the sagittal plane, with substantially smaller available ranges of motion in the transverse and fontal planes. The quadriceps muscles, particularly the vastus lateralis, 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 a flexor and extensor, respectively. These two muscle groups primarily cross longitudinally, 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 position. Forceful quadriceps contractions at small knee flexion angles contribute to anterior shear force at the proximal tibia, whereas hamstring contractions exert a posterior shear force. Along with several other muscles crossing the knee, the quadriceps and hamstrings contribute to frontal plane motion and stability [53]; 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, especially during weight-bearing activities. Not surprisingly, the hip is implicated in several acute and overuse injuries of the knee.

ACL Injury

ACL injuries occur when the load-bearing capacity of the ligament is exceeded. Although these loads may result from direct contact to the knee, ACL injury mechanisms that do not involve contact are of particular concern because their etiology is less clear. It has been reported that as many as 70 % of ACL injuries occur as a result of noncontact mechanisms [4, 7, 37]. In these cases, a combination of altered knee positions and torques led to increased loads in the ligament and ultimately failure. The question arises of what contributes to these altered positions and torques?

An extensive body of literature concerning the identification of factors that place individuals at increased risk for ACL injury exists. An appreciation of the factors related to dynamic situations is particularly important because these factors may be more amenable to intervention. Therefore, this chapter will focus on proximal biomechanical and neuromuscular factors directly related to performance of athletic tasks. In particular, much of the evidence presented will be related to landing and

Calculation of Joint Moments
Lower extremity joint moments are 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.

Internal Versus External Moments
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.

Hip Moment Example
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. 10.1a 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.

Knee Moment Example
This can be confusing when referring to the knee in the frontal plane. As seen in Fig. 10.1b 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, *rGRFC* resultant, GRF vector, *COP* center of pressure.

cutting (change of direction) activities because noncontact injuries generally occur during tasks that involve some form of deceleration and/or change of direction [4, 37]. Proximal movement patterns (i.e., joint positions and torques or moments) associated with increased knee loading will be described in the context of biomechanical risk factors (Fig. 10.1), whereas control strategies associated with these movement patterns will be

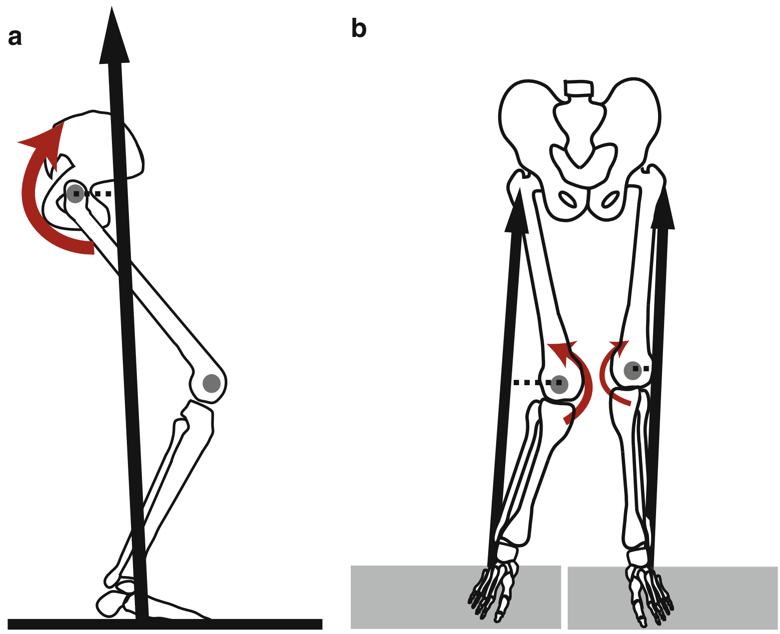


Fig. 10.1 (**a**) Sagittal and (**b**) frontal views of the lower extremity during a squat. *Black arrows* represent the resultant ground reaction force vector. *Dotted lines* represent the moment arm for the ground reaction force. *Red arrows* represent the internal joint moments

discussed in the context of neuromuscular factors. Importantly, these factors are interrelated and must be addressed together in the context of injury prevention training.

Given the increased risk of ACL injuries in female athletes, most of the theories regarding potential risk factors are based on differences attributed to gender. An argument for a particular risk factor is strengthened if that factor is observed in a population thought to be at greater risk for ACL injury (females) and not seen in a population at less risk for injury (males). This chapter will present what is known with respect to gender differences in proximal biomechanical and neuromuscular risk factors and discuss how these factors influence knee loading.

Critical Points

- 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.
- Owing to its anatomy and position in the kinetic chain, the knee is vulnerable to excessive frontal and transverse plane motions of the hip.
- Proximal risk factors are best understood in the context of biomechanical and neuromuscular risk factors

Biomechanical Risk Factors

Knee

Before discussing proximal risk factors for injury, the authors will review what is known regarding the biomechanical risk factors at the knee. The ACL's primary function is to resist internal tibial rotation and anterior tibial translation; it is considered a secondary restraint to knee abduction. In vitro and modeling studies suggest that excessive knee abduction (valgus) and tibial rotation [18], combined with large knee adductor moments (also referred to as knee valgus moment) [17, 32] and increased anterior shear force [11], result in increased and potentially injurious load 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°). This is consistent with injury mechanisms described from videotape and questionnaire analyses that show noncontact ACL injuries occur when the knee is in relative extension, rotation, and valgus. Women have been reported to perform athletic maneuvers with less knee flexion and greater quadriceps activation, knee valgus angles, and knee adductor (valgus) moments compared to men [15, 33, 41, 44, 51]. These strategies are thought to place female athletes at an increased risk for injury. The strongest support for biomechanical risk factors at the knee comes from a prospective study that found increased knee adductor (valgus) moments during a drop-land task showed a statistical relationship to ACL injury risk in female athletes [21]. Currently, anterior tibial force and frontal plane loading are considered the primary loading mechanisms responsible for noncontact ACL injuries.

Hip

Gender Differences in Hip Mechanics

Gender differences in hip mechanics during a variety of functional tasks suggest females limit engagement of the hip in the sagittal plane and rely more heavily on the frontal and transverse planes. During tasks that require double-limb support, females have been found to adopt a more erect posture compared to males, characterized by less hip flexion during landing [41] and vertical stop-jump tasks [5, 51]. This is consistent with studies that evaluated lower extremity energetics during landing. These investigations suggest that females tend to rely less on the hip extensors for sagittal plane shock absorption during landing than males [9, 46]. Engagement of the hip extensors is important for modifying the magnitude of impact forces [13] during landing. Limited involvement of the hip may increase the demand to knee extensors to attenuate impact forces. Gender differences in shock attenuation strategies were highlighted in a recent study that found female athletes exhibited greater knee-to-hip energy absorption and knee-to-hip extensor moment ratios than males during a drop-land task [46]. The higher ratio in women is indicative of a strategy that relies more heavily on knee extensors relative to the hip extensors to attenuate impact forces during landing. Similar gender differences in sagittal plane mechanics have been observed during single-leg landing [42] and side-step cutting tasks [30, 33, 39], suggesting that females do not use their hip extensors to decelerate as much as males.

Examination of hip mechanics during single-limb tasks highlights gender differences in frontal and transverse plane control. During single-limb hopping [22] and squatting [52] tasks, females exhibit greater hip adduction than males. The finding of increased hip adduction suggests that females do not stabilize their pelvis in the frontal plane during these tasks. This is supported by gender differences in running kinematics. Ferber and colleagues [14] found that women exhibited greater peak hip adduction and internal rotation during running compared to men. In addition, Pollard et al. [39] reported that female collegiate athletes used greater hip internal rotation and larger hip adductor moments compared to their male counterparts to perform a 45° side-step cutting task. This pattern was of particular significance because the women also demonstrated greater knee adductor (valgus) moments [44].

Together, these data support the notion that female athletes tend to adopt a pattern of sagittal plane avoidance, with an increased reliance on the transverse and frontal planes during both double- and single-limb tasks.

Influence of the Hip on Knee Mechanics

Stronger support for proximal risk factors comes from studies that show a relationship between hip mechanics and biomechanical risk factors at the knee. These relationships are particularly important if they are present during high-risk activities such as forceful cutting, change of direction, or when landing from a jump.

A potential link between injurious knee loading and what occurs at the hip was first proposed by Ireland [26, 27] who described the "position of no return," a combination of lower extremity positions that would ultimately lead to ACL injury (see also Chap. 11). This position described an association between excessive internal rotation and adduction at the hip, knee valgus, and knee external rotation. While this lower extremity position was based on observation and experience, it highlighted the importance of the potential role of the hip in ACL injury. A greater appreciation of the influence of the hip on the knee has gained support in recent years, with studies describing the relationship between hip and knee mechanics during dynamic tasks.

Landing Mechanics

There is evidence to suggest that the sagittal plane shock absorption strategy demonstrated by female athletes during landing reflects a biomechanical pattern that places greater mechanical loads on the knee joint and perhaps the ACL. A recent study that evaluated landing strategies in 48 female athletes demonstrated this point by comparing lower extremity mechanics according to the degrees of flexion used during a drop-land task [40]. Athletes were divided into two groups, those who performed with above average hip and knee flexion and those who performed the task with below average combined flexion. The athletes in the high flexion group demonstrated, on average, 100° and 90° of peak knee and hip flexion during deceleration, respectively. In contrast, the low flexion group limited their knee and hip flexion to 87° and 67°, respectively. When compared to athletes who used the high flexion strategy, those who used a low flexion strategy exhibited a 10 % increase in average knee extensor moments and a 35 % increase in quadriceps activation during deceleration. It appeared that the athletes who used less hip and knee flexion to decelerate relied heavily on the knee extensors, whereas those who used more hip and knee flexion were able to shift some of the demand away from the knee to the hip. This was illustrated by the considerable differences in knee-to-hip extensor moment ratio and knee-to-hip energy absorption ratios. The low flexion group had 66 and 52 % greater ratios, indicating substantially greater contributions from the knee extensors to attenuate impact forces. This increased demand on the knee extensors is of particular concern with respect to injury risk. Large quadriceps forces are thought to contribute to anterior tibial shear forces and increased loading of the ACL [11]. Specifically, increased anterior tibial shear forces have been noted in individuals who perform a drop-land task with less hip flexion and greater knee flexion range of motion, and greater knee extensor moments and quadriceps activation [43]. After accounting for the effects of gender, these variables combine to explain 57 % of the variance in anterior shear force during a drop-land task.

Several biomechanical factors associated with landing strategies that limit hip and knee flexion, typically referred to as "stiff landing," contribute to greater knee loading. "Stiff" or low flexion landing results in greater vertical ground reaction forces [13] when compared to "soft" or high flexion landing. This combined with reduced lower extremity excursions leads to increased loading rates and decreased shock attenuation. In addition, limited hip flexion results in a more erect trunk posture. This shifts the center of mass posteriorly and increases the lever arm for the vertical ground reaction force at the knee in the sagittal plane (Fig. 10.2a). This in turn increases the intersegmental forces acting to flex the knee. Larger intersegmental forces combined with a larger magnitude ground reaction force results in an increased demand on the knee extensors to attenuate the ground reaction forces. In contrast, greater hip flexion (Fig. 10.2b) 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

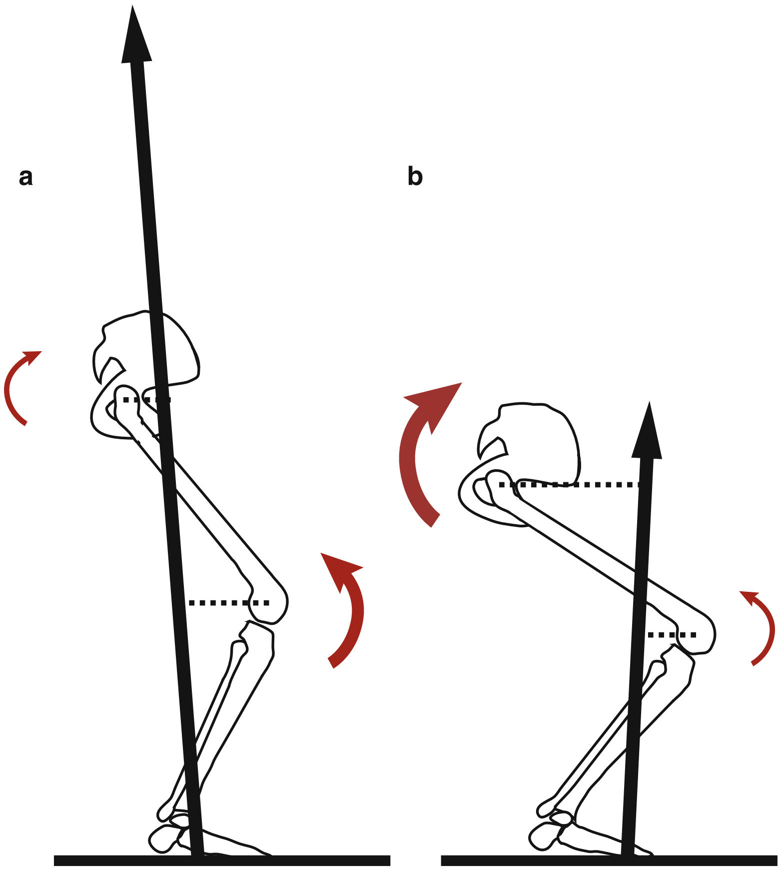


Fig. 10.2 (**a**) The influence of hip flexion on sagittal plane hip and knee moments during landing. Limited hip flexion during landing shifts the resultant ground reaction force vector (*black arrow*) posterior; closer to the hip joint center and further from the knee joint center (*gray circles*). 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*) at the hip and knee, 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 form 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 demand on the knee extensors

utilization of the knee and hip extensors. A more even distribution coupled with a smaller magnitude ground reaction force ultimately decreases the demand on the knee extensors and reduces the anterior tibial shear force.

While these figures illustrate the potential biomechanical effects of hip flexion angle on sagittal plane knee loading during landing, they represent an oversimplification of a dynamic task. In these figures, only one potential combination of hip and knee flexion angles is considered at a single point in time. It is important to understand the motion of the hip and knee and coordination between the joints throughout the task. For example, Yu and colleagues [51] found that angular velocities of the hip and knee at initial contact of a stop-jump task were associated with ground reaction forces, while joint positions were not. Greater hip flexion angular velocity was associated with reduced posterior and vertical ground reaction forces. It was not the position of the hip and knee flexion, but active hip and knee flexion that reduced impact forces during deceleration. Furthermore, Hashemi and colleagues [20] suggested that the coordination of hip and knee flexion is also important. They proposed that if the hip flexes more slowly than the knee during deceleration, the tibia will undergo anterior translation and increase the load on the ACL in the absence of appropriate muscular control. 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 the influence on sagittal plane knee loading, hip mechanics play a critical role in knee frontal plane loading. This is important because knee valgus angles and knee adductor (valgus) moments have been statistically associated with ACL injury. It is not surprising that hip and knee frontal plane angles are related during bilateral landing tasks. Hip adduction angle is strongly correlated with knee valgus angle [46]. Sigward and colleagues [46] found a positive correlation between hip frontal plane angle and knee valgus during a bilateral drop-land task, indicating that greater hip adduction is associated with greater knee valgus. While not as consistent across all single-limb tasks, an association between hip adduction and knee valgus angles has also been identified during single-limb step-down tasks [24].

While these findings highlight the interdependence of the hip and knee joints in the frontal plane, it appears that sagittal plane loading strategies also play a role in frontal plane knee mechanics. Use of a "stiff" landing strategy has been associated with greater frontal plane loading of the knee. Specifically, Pollard and colleagues [40] found that females who used a "stiff" landing strategy exhibited greater knee valgus angles and knee adductor (valgus) moments. Knee adductor (valgus) moments were 2.2 times greater in a group of athletes who limited their hip and knee flexion during landing compared to those who used a "soft" landing strategy. As illustrated in Fig. 10.3, the athlete that limits hip and knee flexion during landing exhibits greater apparent knee abduction (Fig. 10.3a) whereas the athlete that flexes through the hips and knees maintains a more neutral knee position (Fig. 10.3b). Decreased engagement of the hip extensor, indicated by a 66 and 52 % greater knee-to-hip extensor moment and energy absorption 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.

Critical Points

- Increased hip flexion during landing engages the hip extensors and decreases the demand on the knee extensors to attenuate impact forces.
- Hip adduction and internal rotation are related to knee abduction (valgus) and adductor (valgus) loading during single- and double-limb 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.

Cutting Mechanics

Associations between hip and knee mechanics have also been identified during athletic cutting or change of direction tasks. However, the relationship in these mechanics in the frontal plane is different than that described during landing. During landing, hip adduction and internal rotation are associated with increased knee frontal plane knee loading. In contrast, it appears that hip

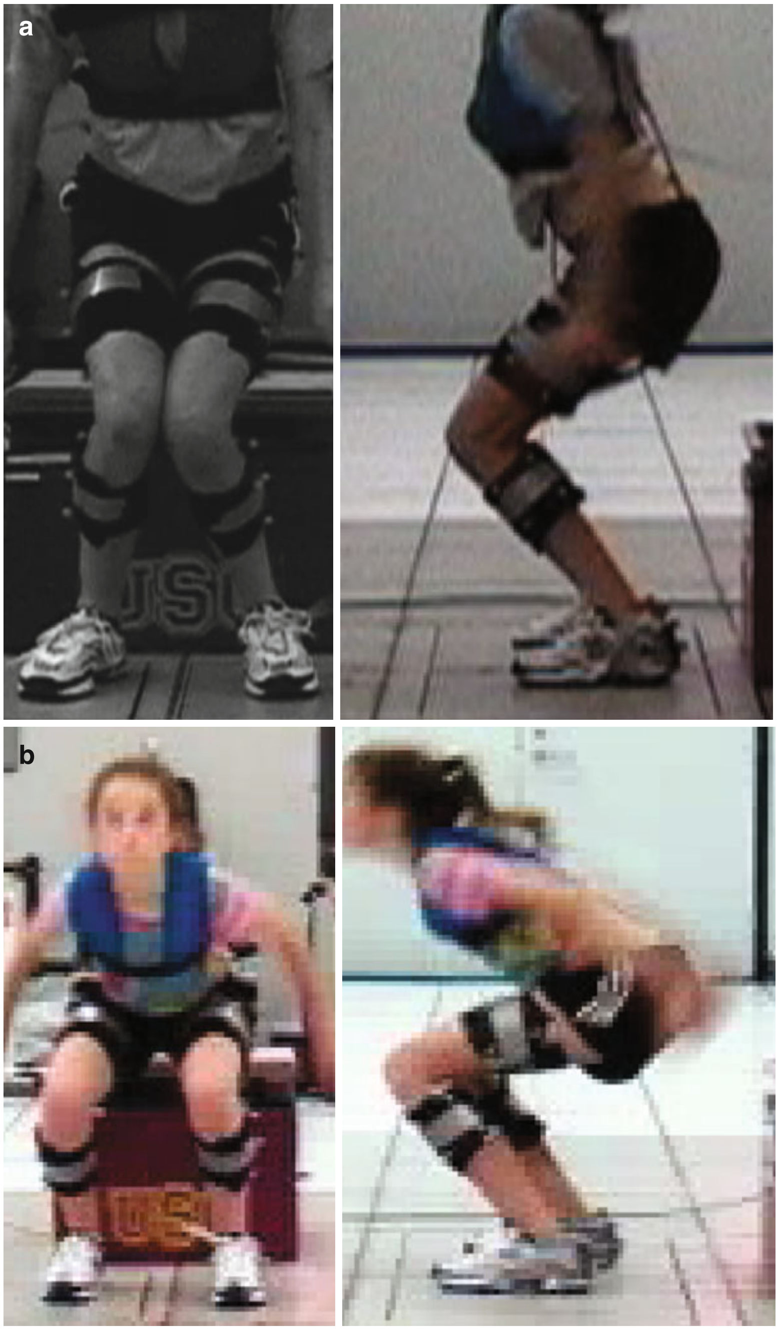


Fig. 10.3 Sagittal and frontal plane kinematics associated with a "stiff" (**a**) and "soft" (**b**) landing strategy. The athlete using a "stiff" landing strategy with less hip and knee flexion also exhibits greater knee abduction (**a**), whereas the athlete that is flexing through the hips and knees maintains a more neutral frontal plane position at the knee (**b**) (Reprinted with permission from Pollard et al. [40])

abduction and internal rotation contribute to increased knee frontal plane loading during cutting [19, 34, 45]. This is true for cutting tasks that involve a change in direction away from the stance limb (side-step cutting). These task differences are likely due to the different demands placed on the hip with respect to mobility and regulation of the upper body. During landing, trunk and hip flexion work to decelerate and absorb primarily vertical ground reaction forces. In contrast, cutting requires greater horizontal deceleration of the forward progression of the

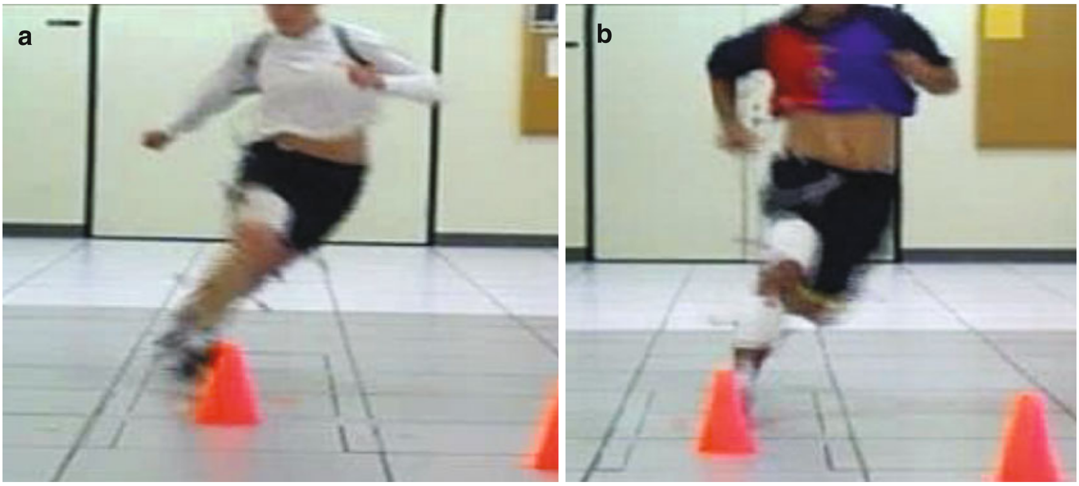


Fig. 10.4 Hip mechanics associated with knee adductor (valgus) moments during cutting. When compared to the athlete in (**b**), the athlete in (**a**) is positioned in greater hip abduction, hip internal rotation, and a more internally rotated foot position. This strategy engages hip adductors and limits the demand on the hip abductors. Along with a more laterally directed ground reaction force, these factors are correlated to greater knee adductor (valgus) moments (Reprinted with permission from Pollard et al. [39])

body, along with redirection and reorientation into the new direction. These different postural demands result in different hip and knee loading relationships.

During side-step cutting, knee adductor (valgus) moments have been associated with hip abduction, hip internal rotation, and an internally rotated foot position at initial contact (Fig. 10.4) [45]. Greater hip abduction suggests that these athletes reach out laterally with their foot at initial contact. This is of concern because larger hip abduction angles have been found to be related to larger knee valgus angles during side-step cutting [25]. Moreover, a more lateral placement of the stance limb away from the body results in larger knee adductor (valgus) moments [12, 19]. Compared to running, peak knee adductor (valgus) moments can increase almost fourfold during cutting tasks performed with a larger step width (~60 cm) [19]. Even small increases in step width (~15 cm) have been reported to result in a 37 % increase in knee moments when compared to cutting performed with no step width alterations [12]. Hip and limb internal rotation have also been associated with an increase in frontal plane loading of the knee. Sigward and Powers [45] found that when compared to female athletes with smaller knee adductor (valgus) moments, those with larger moments adopted a strategy that included twice as much hip internal rotation and a more internally rotated foot. Moreover, both variables were correlated with increased knee adductor (valgus) moments [45]. This is consistent with differences observed between the sexes. Female collegiate athletes who exhibited greater knee adductor (valgus) moments used a strategy that included greater hip internal rotation compared to their male counterparts [39, 45]. Similar to what was observed in female athletes, a relationship between knee adductor (valgus) moments and hip internal rotation was also observed in a cohort of male and female athletes. However, there is evidence that knee adductor (valgus) moments are more sensitive to changes in hip rotation in females during cutting than males [34].

In contrast to the demands of landing, cutting tasks are such that an individual must decelerate the forward progression of the center of mass and change directions. Both rotation of the body and lateral translation of the center of mass toward the new direction are required for a successful change of direction [23]. It appears that prepositioning

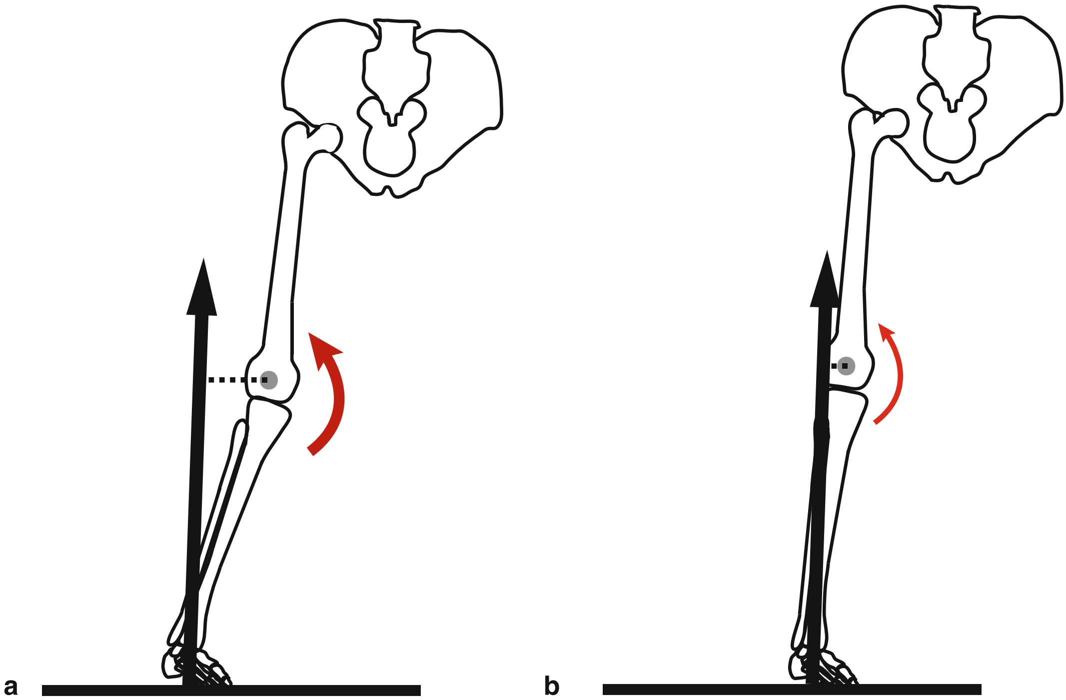


Fig. 10.5 The contribution of hip abduction to knee adductor (valgus) internal moments during cutting. Increased hip abduction (**a**) moves the center of pressure (located in the foot) laterally with respect to the center of mass gray circle, creating a larger moment arm (*dotted line*) for the vertical ground reaction force (*black arrow*) 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**)

the hip in internal rotation assists in rotating the body into the new direction. Hip abduction facilitates lateral translation of the center of mass in the new direction by placing the stance limb lateral to the body's center of mass and, in turn, increasing the acceleration of the body in the opposite direction [38]. This strategy reduces the demands on the hip and knee extensors to control motion during deceleration, and reduces the demand on the hip abductors and external rotators to stabilize the pelvis during deceleration and to drive the body into the new direction. Similar to landing, this strategy appears to limit engagement of the larger hip extensors and abductors.

These alterations in hip position contribute to increased knee adductor (valgus) moments by altering the relationship between the body's center of mass (COM) and the center of pressure (COP). For instance, when considering hip abduction, greater abduction moves the center of pressure more lateral to the center of mass (Fig. 10.5). This creates a larger lever arm for the vertical ground reaction force (GRF) in the frontal plane, thereby increasing 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 will also contribute to 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 [45]. The lateral GRF imposes a large laterally directed intersegmental force to the distal end of the tibia, further contributing to a larger knee adductor (valgus) moment at the knee. 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 [12].

Critical Points

- Biomechanics at the hip are related to knee loading, and the relationship varies based on the demands of the task.
- Hip abduction and internal rotation are related to knee abduction and adductor (valgus) loading during cutting.
- Greater hip abduction and internal rotation at initial contact during cutting appears to limit engagement of the hip abductors.

Neuromuscular Risk Factors

In the previous section, the influence of the hip mechanics was discussed on potentially injurious joint knee loading. This section will focus on factors related to the control of these strategies. 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., altered control strategies).

Muscle Strength

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 range of motion, strength, or power needed to complete the task. Adequate strength is needed 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.

Gender Differences in Hip Strength

Gender differences in hip strength suggest that, after accounting for body mass, females are weaker than males when considering hip abductors, external rotators, and extensors. Isokinetic strength testing reveal that young, recreationally athletic males generate 30 % greater hip abductor and 40 % greater external rotator eccentric peak torque than their female counterparts [1]. Despite the recent increase in attention to the role of the hip extensor (gluteus maximus) in attenuating impact forces and controlling hip rotation, only one study has compared strength between genders. Claiborne and colleagues [6] found that males generated greater eccentric and concentric hip extension than females, although only eccentric differences reached significance. Eccentric strength deficits are of particular concern for injury risk given that noncontact ACL injuries occur more frequently during deceleration of dynamic tasks. Interestingly, gender differences in hip abductor and external rotator strength have also been detected using isometric strength testing with a handheld dynamometer [31, 49]. This suggests that clinical screening for strength deficits using isometric testing may be suitable for strength screening. While gender differences suggest that proximal weakness may be a risk factor for injury, stronger support comes from the association between strength and injury and lower extremity mechanics.

Relationship Between Hip Strength and Knee Pathology

Studies linking hip weakness and knee pathology provide some support for a potential relationship between hip muscle function and knee injury. Several recent studies have related hip weakness to lower extremity injuries [16,28,31,36]. Individuals diagnosed with iliotibial band syndrome [16], patellofemoral pain [28,47], and lower extremity overuse injuries related to running [36] were found to have ipsilateral deficits in hip strength. While a cause and effect relationship between hip strength and lower extremity injury cannot be assumed based on these data, a prospective study provides some evidence to support this link. Leetun and colleagues [31] evaluated hip strength in 140 male and female collegiate athletes prior to their sports season. Those athletes who sustained a lower extremity injury during the season were found to have decreased hip abductor and external rotator strength when compared to those who were not injured. Furthermore, hip external rotation strength was found to be a predictor of injury status.

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. 10.6a). In addition, compensatory trunk lean over the stance limb is also thought to reduce the demand on the hip abductors (Fig. 10.6b). These compensations were related to hip abductor strength in a recent study that examined the association between eccentric hip abductor strength and hip kinematics during a single-limb squat [2]. Baldon Rde and colleagues [2] found that decreased eccentric hip abductor strength was related to greater femur adduction and internal rotation during a single-leg squat. These relationships held true for females, but not for males. These results were supported by a recent clinical study conducted by Crossley and colleagues [8] who found that observational assessments of limb and trunk posture were related to isometric hip abductor strength. Trained clinicians visually assessed trunk, pelvis, femur, and knee posture in 34 individuals performing the squat. Using criterion typically used in the clinic, the investigators rated the test result as good if the subject demonstrated no trunk deviations, a level pelvis, a neutral hip position in the transverse and frontal planes, and no medial knee deviation. When compared to subjects who performed the task well, those who were rated as poor had a 29 % decrease in hip abductor strength. These data suggest that observational analysis of compensatory patterns may be an appropriate way to screen for hip abductor weakness.

Poor hip muscle function has also been related to increased knee frontal plane motion. Associations between hip abductor [2, 6] and external rotator strength [49] and knee valgus have been noted during the single-limb squat test. 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 [29]. A similar (but much weaker) relationship was found in a larger sample size. A recent study evaluating 2,753 cadets reported that while hip external rotator strength was related to poor landing mechanics, it only had minimal influence [3]. Although relationships between strength and lower extremity mechanics have been noted in these studies, other investigations failed to find these relationships [44]. In addition, no study has found a relationship between hip strength and lower extremity mechanics during cutting maneuvers, suggesting that muscle strength is not the only factor contributing to potentially injurious lower extremity mechanics. 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 is relatively weak. The weak relationship may be due to the manner in which strength is being tested. More comprehensive measures of muscle function may reveal more robust relationships [47].

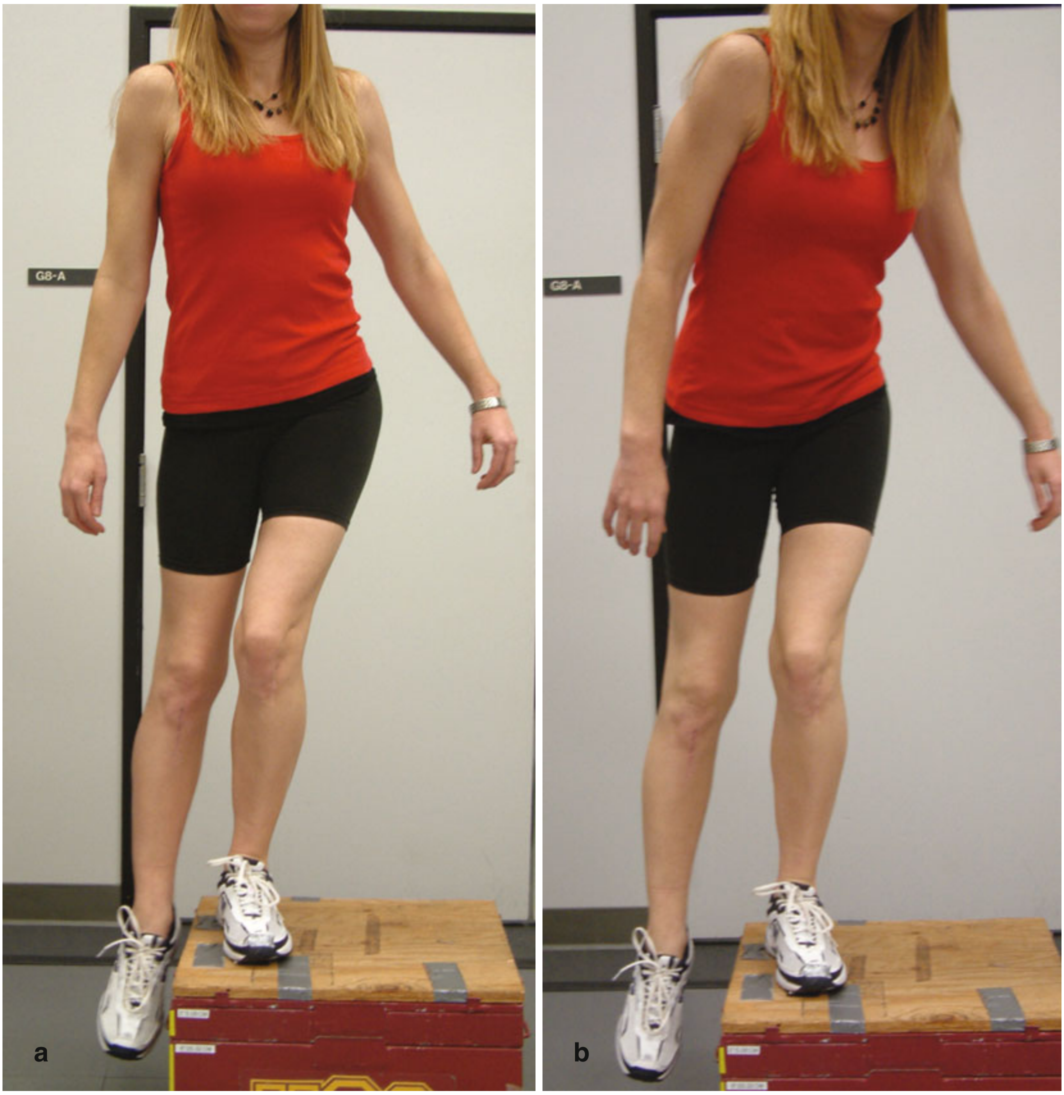


Fig. 10.6 Poor pelvifemoral control attributed to hip abductor weakness. (**a**) An individual with poor hip abductor function can exhibit excessive hip adduction, internal rotation, and contralateral pelvic drop. (**b**) Medial collapse of the femur is not as apparent if the individual compensates for hip abductor weakness by leaning the trunk over the stance limb

Motor 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 and colleagues [35] 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, 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. A recent study found an association between gluteal muscle activation timing (onset) and hip adduction and internal rotation excursion in females with patellofemoral joint pain during running [50]. Greater joint excursions were correlated with a delay onset of muscle contraction. A similar relationship was noted in asymptomatic individuals during a single-leg squat [8]. Individuals rated as good based on trunk and pelvic posture, and 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 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; it may be important to consider both factors during training.

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 if it 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 preplanned 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, as 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, it is important not to neglect the transverse and frontal plane demands of athletic tasks. 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).

References

1. Baldon Rde M, Nakagawa TH, Muniz TB et al (2009) Eccentric hip muscle function in females with and without patellofemoral pain syndrome. J Athl Train 44(5):490–496
2. Baldon Rde M, Lobato DF, Carvalho LP et al (2011) Relationship between eccentric hip torque and lower-limb kinematics: gender differences. J Appl Biomech 27(3):223–232
3. Beutler A, de la Motte S, Marshall S et al (2009) Muscle strength and qualitative jump-landing differences in male and female military cadets: the jump-ACL study. J Sports Sci Med 8:663–671
4. Boden BP, Dean GS, Feagin JA Jr et al (2000) Mechanisms of anterior cruciate ligament injury. Orthopedics 23(6):573–578
5. Chappell JD, Creighton RA, Giuliani C et al (2007) Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury. Am J Sports Med 35(2): 235–241
6. Claiborne TL, Armstrong CW, Gandhi V et al (2006) Relationship between hip and knee strength and knee valgus during a single leg squat. J Appl Biomech 22(1):41–50
7. Cochrane JL, Lloyd DG, Buttfield A et al (2007) Characteristics of anterior cruciate ligament injuries in Australian football. J Sci Med Sport 10(2):96–104
8. Crossley KM, Zhang WJ, Schache AG et al (2011) Performance on the single-leg squat task indicates hip abductor muscle function. Am J Sports Med 39(4): 866–873
9. Decker MJ, Torry MR, Wyland DJ et al (2003) Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. Clin Biomech (Bristol, Avon) 18(7):662–669
10. Delp SL, Hess WE, Hungerford DS et al (1999) Variation of rotation moment arms with hip flexion. J Biomech 32(5):493–501
11. DeMorat G, Weinhold P, Blackburn T et al (2004) Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. Am J Sports Med 32(2):477–483
12. Dempsey AR, Lloyd DG, Elliott BC et al (2007) The effect of technique change on knee loads during sidestep cutting. Med Sci Sports Exerc 39(10):1765–1773
13. Devita P, Skelly WA (1992) Effect of landing stiffness on joint kinetics and energetics in the lower extremity. Med Sci Sports Exerc 24(1):108–115
14. Ferber R, Davis IM, Williams DS 3rd (2003) Gender differences in lower extremity mechanics during running. Clin Biomech (Bristol, Avon) 18(4): 350–357
15. Ford KR, Myer GD, Smith RL et al (2006) A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. Clin Biomech (Bristol, Avon) 21(1):33–40
16. Fredericson M, Cookingham CL, Chaudhari AM et al (2000) Hip abductor weakness in distance runners with iliotibial band syndrome. Clin J Sport Med 10(3):169–175
17. Fukuda Y, Woo SL, Loh JC et al (2003) A quantitative analysis of valgus torque on the ACL: a human cadaveric study. J Orthop Res 21(6):1107–1112
18. Fung DT, Hendrix RW, Koh JL et al (2007) ACL impingement prediction based on MRI scans of individual knees. Clin Orthop Relat Res 460:210–218
19. Golden GM, Pavol MJ, Hoffman MA (2009) Knee joint kinematics and kinetics during a lateral false-step maneuver. J Athl Train 44(5):503–510
20. Hashemi J, Breighner R, Chandrashekar N et al (2011) Hip extension, knee flexion paradox: a new mechanism for non-contact ACL injury. J Biomech 44(4): 577–585
21. Hewett TE, Myer GD, Ford KR et al (2005) Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med 33(4):492–501
22. Hewett TE, Ford KR, Myer GD et al (2006) Gender differences in hip adduction motion and torque during a single-leg agility maneuver. J Orthop Res 24(3):416–421
23. Hollands MA, Sorensen KL, Patla AE (2001) Effects of head immobilization on the coordination and control of head and body reorientation and translation during steering. Exp Brain Res 140(2):223–233
24. Hollman JH, Ginos BE, Kozuchowski J et al (2009) Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. J Sport Rehabil 18(1):104–117
25. Imwalle LE, Myer GD, Ford KR et al (2009) Relationship between hip and knee kinematics in athletic women during cutting maneuvers: a possible link to noncontact anterior cruciate ligament injury and prevention. J Strength Cond Res 23(8):2223–2230

26. Ireland ML (1999) Anterior cruciate ligament injury in female athletes: epidemiology. J Athl Train 34(2): 150–154
27. Ireland ML (2002) The female ACL: why is it more prone to injury? Orthop Clin North Am 33(4): 637–651
28. Ireland ML, Willson JD, Ballantyne BT et al (2003) Hip strength in females with and without patellofemoral pain. J Orthop Sports Phys Ther 33(11): 671–676
29. Jacobs C, Uhl TL, Seeley M et al (2005) Strength and fatigability of the dominant and nondominant hip abductors. J Athl Train 40(3):203–206
30. Landry SC, McKean KA, Hubley-Kozey CL et al (2007) Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. Am J Sports Med 35(11):1888–1900
31. Leetun DT, Ireland ML, Willson JD et al (2004) Core stability measures as risk factors for lower extremity injury in athletes. Med Sci Sports Exerc 36(6):926–934
32. Markolf KL, Gorek JF, Kabo JM et al (1990) Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. J Bone Joint Surg Am 72(4):557–567
33. McLean SG, Lipfert SW, van den Bogert AJ (2004) Effect of gender and defensive opponent on the biomechanics of sidestep cutting. Med Sci Sports Exerc 36(6):1008–1016
34. McLean SG, Huang X, van den Bogert AJ (2005) Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. Clin Biomech (Bristol, Avon) 20(8):863–870
35. Mizner RL, Kawaguchi JK, Chmielewski TL (2008) Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. J Orthop Sports Phys Ther 38(6):353–361
36. Niemuth PE, Johnson RJ, Myers MJ et al (2005) Hip muscle weakness and overuse injuries in recreational runners. Clin J Sport Med 15(1):14–21
37. Olsen OE, Myklebust G, Engebretsen L et al (2004) Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am J Sports Med 32(4):1002–1012
38. Patla AE, Adkin A, Ballard T (1999) Online steering: coordination and control of body center of mass, head and body reorientation. Exp Brain Res 129(4):629–634
39. Pollard CD, Sigward SM, Powers CM (2007) Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. Clin J Sport Med 17(1):38–42
40. Pollard CD, Sigward SM, Powers CM (2010) Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. Clin Biomech (Bristol, Avon) 25(2):142–146
41. Salci Y, Kentel BB, Heycan C et al (2004) Clin Biomech (Bristol, Avon) 19(6):622–628
42. Schmitz RJ, Kulas AS, Perrin DH et al (2007) Sex differences in lower extremity biomechanics during single leg landings. Clin Biomech (Bristol, Avon) 22(6):681–688
43. Shultz SJ, Nguyen AD, Leonard MD et al (2009) Thigh strength and activation as predictors of knee biomechanics during a drop jump task. Med Sci Sports Exerc 41(4):857–866
44. Sigward SM, Powers CM (2006) The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. Clin Biomech (Bristol, Avon) 21(1):41–48
45. Sigward SM, Powers CM (2007) Loading characteristics of females exhibiting excessive valgus moments during cutting. Clin Biomech (Bristol, Avon) 22(7):827–833
46. Sigward SM, Pollard CD, Powers CM (2011) The influence of sex and maturation on landing biomechanics: implications for anterior cruciate ligament injury. Scand J Med Sci Sports 22(4):502–509
47. Souza RB, Powers CM (2009) Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. J Orthop Sports Phys Ther 39(1):12–19
48. Ward SR, Eng CM, Smallwood LH et al (2009) Are current measurements of lower extremity muscle architecture accurate? Clin Orthop Relat Res 467(4): 1074–1082
49. Willson JD, Ireland ML, Davis I (2006) Core strength and lower extremity alignment during single leg squats. Med Sci Sports Exerc 38(5):945–952
50. Willson JD, Kernozek TW, Arndt RL et al (2011) Gluteal muscle activation during running in females with and without patellofemoral pain syndrome. Clin Biomech (Bristol, Avon) 26(7):735–740
51. Yu B, Lin CF, Garrett WE (2006) Lower extremity biomechanics during the landing of a stop-jump task. Clin Biomech (Bristol, Avon) 21(3):297–305
52. Zeller BL, McCrory JL, Kibler WB et al (2003) Differences in kinematics and electromyographic activity between men and women during the single-legged squat. Am J Sports Med 31(3): 449–456
53. Zhang LQ, Xu D, Wang G et al (2001) Muscle strength in knee varus and valgus. Med Sci Sports Exerc 33(7):1194–1199

Gender Differences in Core Strength and Lower Extremity Function During the Single-Leg Squat Test

11

Mary Lloyd Ireland, Thomas Durbin,
and Lori A. Bolgla

Contents

M.L. Ireland, M.D. (✉) • T. Durbin, M.D.
Department of Orthopaedic Surgery & Sports Medicine, University of Kentucky, KY Sports Medicine Perimeter, 601 Perimeter Dr, Ste 200, Lexington, KY 40517, USA
e-mail: mary.ireland@uky.edu; thomas.durbin@uky.edu

L.A. Bolgla, P.T., Ph.D., A.T.C.
Department Physical Therapy, College Allied Health Sciences, Georgia Health Sciences University, EC-1334, Augusta, GA 30912, USA
e-mail: lbolgla@georgiahealth.edu

Introduction

Anterior cruciate ligament (ACL) injury is one of the most serious and costly knee injuries sustained by female athletes [48]. It has been estimated that orthopedic surgeons perform approximately 100,000 ACL reconstructions each year in the United States [48]. Irrespective of the costs associated with diagnostic testing and rehabilitation, Lubowitz and Appleby [28] recently reported a cost per case of $12,740 for hospital and professional fees. More compelling is the fact that recent evidence has suggested that athletes who incur ACL injury have a higher probability of developing knee osteoarthritis [27, 51]. Based on these emerging data, researchers have directed much attention toward the development and implementation of ACL injury prevention programs [17, 30, 34].

Over 70 % of all ACL injuries in soccer and basketball occur via a noncontact mechanism [2]. During these sports, women commonly incur this injury when performing an open cutting maneuver which 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" [18, 29]. Using a cadaveric model, Fung and Zhang [15] demonstrated how dynamic knee valgus can impart excessive strain of the ACL over the lateral femoral condyle.

ACL injury etiology in the female athlete is a multifactorial problem that may result from

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_11, © Springer-Verlag Berlin Heidelberg 2012

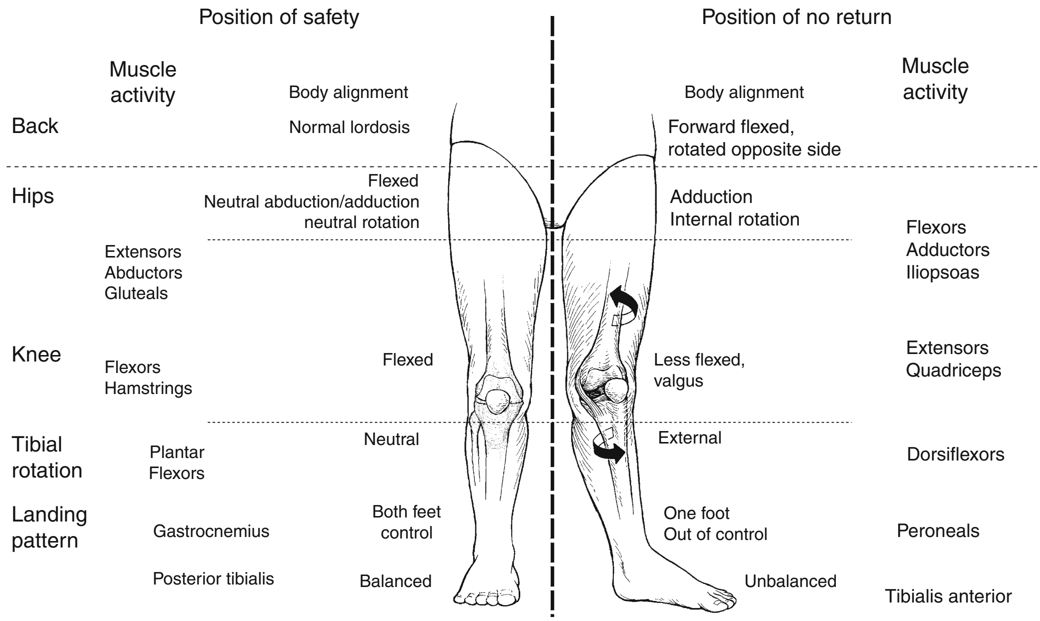


Fig. 11.1 Muscle activity and body alignment is shown for the position of safety (*left*) and "position of no return" (*right*). The position of safety occurs with knee flexed, hip flexed and neutral, and two-footed balanced landing. In contrast, the "position of no return" occurs when the body is more upright with the hips and knees less flexed, resulting in uncontrolled body rotation when landing. The muscle imbalance and position of trunk and joints place knee at risk for ACL tear

anatomical/structural, hormonal, neuromuscular, and biomechanical factors [47]. 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 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 [20] described the "position of no return" shown in Fig. 11.1. The safe position (shown on the left) incorporates a more flexed hip and knee position which facilitates muscles of hip external rotation, 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 adduction/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 the position of no return, it is hypothesized that there is an uncontrolled landing with a rapid whiplike action on a fixed pronated foot with the tibia externally rotated. Axial loading occurs when the femur whips into an internally rotated position and ACL injury occurs. According to this model, women often perform athletic maneuvers with increased trunk flexion that can reduce pelvic stability. Reduced pelvic stability in turn may cause increased hip adduction and hip internal rotation. Together, these combined motions may lead to increased knee valgus loading, making the female athlete more susceptible to injury [18].

For over 10 years, researchers have examined the interaction between hip and knee mechanics in the female athlete and reported faulty hip mechanics compared to males during landing and cutting maneuvers [11, 13, 22, 23, 35]. A limitation of these studies has been the use of expensive,

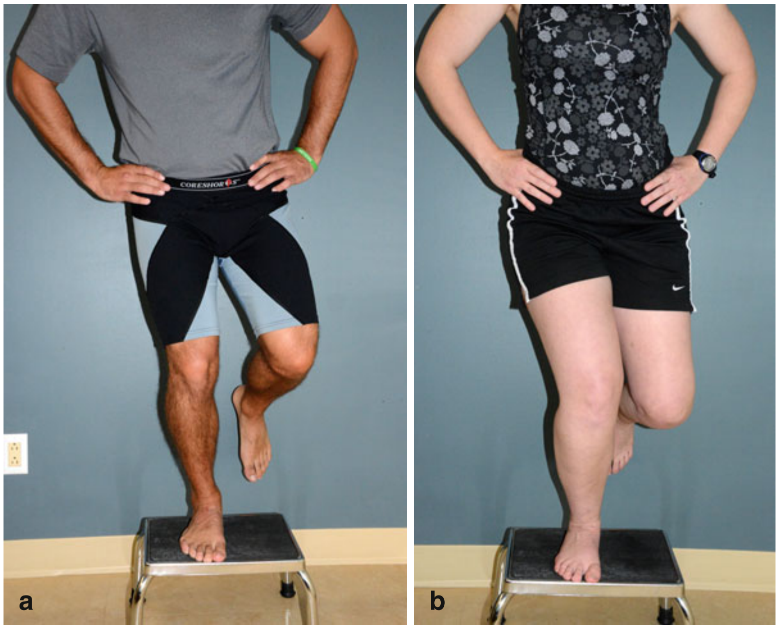


Fig. 11.2 Single-leg mini-squat done while standing on a step. (**a**) The male athlete has good balance, with hip-over-knee-over-ankle control and a level pelvis. (**b**) The female athlete has valgus at the knee, resulting from the proximal body position of femoral internal rotation and adduction, leading to subsequent tibia external rotation and pronation, in order to remain upright doing this maneuver. There is pelvic drop on contralateral side

3-dimensional (3-D) motion analysis systems that are not conducive for a clinical setting. To address this limitation, more recent works have compared 3-D lower extremity measures to frontal plane data collected using more simplistic 2-dimensional (2-D) techniques. 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 [32, 54].

The single-leg squat test represents 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, obvious differences may be seen between males and females as they perform this test. An example is shown in Fig. 11.2a, where the male exhibits proximal control as evidenced by a straight hip-over-knee-over ankle position. In contrast, the female (Fig. 11.2b) 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. 11.3a shows the male demonstrating the preferred lumbar spine position, with a posteriorly rotated pelvis. However, the female (Fig. 11.3b) 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.

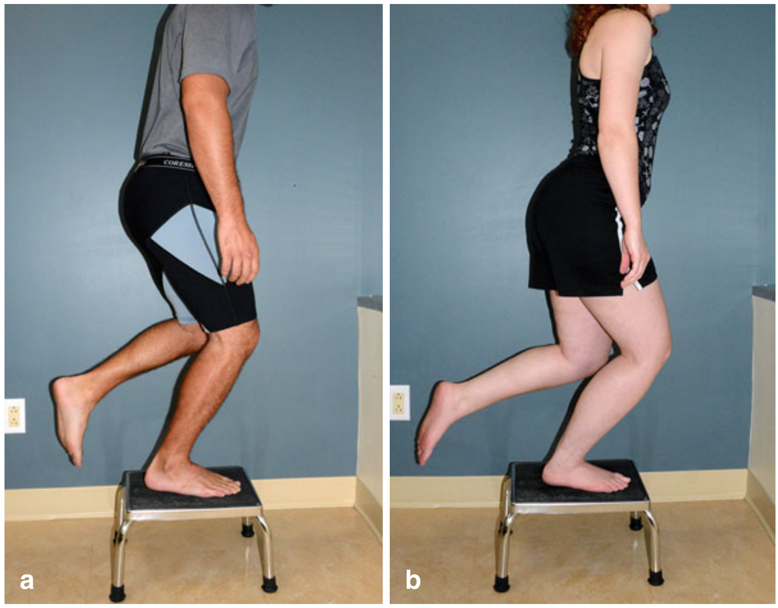


Fig. 11.3 Single-leg mini-squat shown from the side. (**a**) The male demonstrates a more posteriorly rotated pelvis, with the lumbar spine in neutral, and better balance with the knee flexed. (**b**) Female has a forward thoracic-lumbar spine movement with pelvic drop and anterior pelvis rotation

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.

Definition and Principles of Core Stability

Anatomically, the core may be 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 [41] 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 [52]. The active component may provide stability through increased abdominal pressure, spinal compressive forces, and trunk and hip muscle stiffness [52]. If one or more of these restraints are 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 [38]. Cholewicki and VanVliet [6] 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 [19] examined trunk musculature onset during lower extremity movement. Their findings highlighted the importance of abdominal contraction, specifically, the transverse abdominis and the multifidus, in advance of lower extremity movement. They concluded that co-contraction of these antagonist muscle groups increased intra-abdominal pressure to facilitate spinal stiffness [52]. 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 [36]. 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 [43]. The hip external rotators also may play a significant role in stability and injury prevention. Souza and Powers [50] found that hip extensor weakness was a predictor of increased hip internal rotation during running in females with anterior knee pain. Leetun et al. [25] 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.

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

Since core stability involves the interaction of many complex elements, clinical measures are 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 (usually 90°), 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. Although various descriptions of the test exist, all focus on trunk and lower extremity control and position [1, 46, 53, 57]. 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 of the core and hip musculature that may 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 [57]. Increased quadriceps activity, especially with the knee in minimally flexed position, can cause increased anterior tibial translation and strain on the ACL [4, 31].

The usefulness of any clinical tool depends on its reliability and validity. Munro et al. [33] examined the reliability of using the frontal plane projection angle (FPPA) as described by Willson et al. [53] 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. 11.4). These investigators reported between-day intraclass correlation coefficients of 0.88 and 0.72 for males and females, respectively.

Ageberg et al. [1] 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. [1] concurrently collected 3-D motion analysis data. Findings from the 2-D analysis showed that the subjects who received a "knee-medial-to-foot" rating exhibited a greater peak thigh angle (in relation to the horizontal plane) that was more medially orientated relative to the knee. This orientation suggested that these

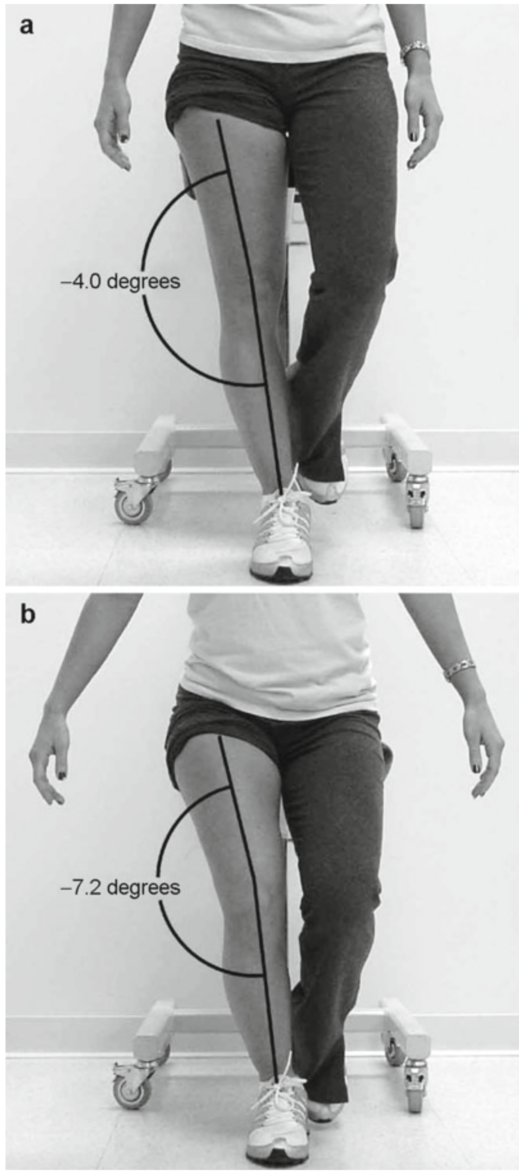


Fig. 11.4 The measurement of the frontal plane projection angles doing a single-leg stance (**a**) and single-leg squat (**b**). The angle is measured between two lines, the midpoint of the knee joint to midpoint of the ankle mortise and on the anterior superior iliac spine to the midpoint of knee joint. 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. [53])

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.

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.

Core Strength and Lower Extremity Function

Willson et al. [53] 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. They reported a significant correlation between increased trunk extension ($r=0.26$; $P=0.05$), trunk lateral flexion ($r=0.27$; $P=0.04$), hip external rotation ($r=0.40$; $P=0.004$), and a neutral FPPA (an angle closer to 0°). Although not significant, a trend existed for the importance of the hip abductors ($r=0.23$; $P=0.07$). Regarding knee strength, the investigators reported a significant correlation between the knee flexors ($r=0.33$; $P=0.02$), but not the knee extensors ($r=0.23$; $P=0.12$), and the FPPA. Although the knee flexors (hamstrings) function primarily as a knee flexor, it is noteworthy that the hamstrings also assist with hip extension. This orientation may account for the significant association found between the knee flexors and FPPA.

Using an isokinetic dynamometer to measure hip and knee strength, Claiborne et al. [7] 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 is 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 11.1).

Although both Willson et al. [53] and Claiborne et al. [7] reported significant associations between isometric strength measures and concentric peak torque and knee valgus during a single-leg squat, correlation coefficients were considered weak to moderate at best [42]. A possible reason for these correlations might have been that these strength measures did not reflect muscle function during this dynamic task. As described above, the hip abductors and external

Table 11.1 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 et al. [3]	Hip abductors	3-dimensional motion analysis of pelvis, femur, and knee	Moderate negative correlation between eccentric hip abductor torque and femur and knee adduction
	Hip external rotators		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. [9]	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 [55]	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

rotators work synergistically in an eccentric manner to control hip adduction, hip internal rotation, and contralateral pelvic drop during weight-bearing activities [36].

To account for this type of muscle demand, Baldon et al. [3] 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 females. 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 females.

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 is noteworthy that correlation coefficients were relatively higher between eccentric hip abductor torque and knee valgus than those reported by prior works [7, 53]. 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 have correlated eccentric contractions of muscle fatigue on lower extremity kinematics by examining the effect of hip muscle fatigue on lower extremity kinematics during a single-leg landing. While some studies [21, 22] have reported altered kinematics following a fatigue protocol, others [16, 39] have not shown this effect. As investigators have not examined this effect during a single-leg squat, future studies are needed to better understand this influence.

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 important, Zazulak et al. [56] assessed trunk control in a group of collegiate athletes and prospectively followed them to determine which athletes incurred a knee injury. They identified decreased trunk control as a significant risk factor for knee injury, especially for the female athlete. As discussed earlier, Leetun et al. [25] also prospectively followed athletes over a competitive season. They reported that 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 [55]. Section "Gender Differences During a Single-Leg Squat" provides additional data with respect to gender differences in core strength and lower extremity function during a single-leg squat.

Core Neuromuscular Activity and Lower Extremity Function

Zeller and colleagues [57] were the first to compare electromyographic (EMG) activity (Table 11.2) and trunk and lower extremity kinematics (Table 11.3) 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 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. They 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.

Table 11.2 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 [57]

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 11.3 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 [57]

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)

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 inferred 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, two times greater quadriceps activity, and over six 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 compete the task. Increased muscle activity most likely reflected increased neural drive compared to males to maintain hip and knee position [5, 37, 49].
- 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. [57] support the "position of no return" [20] 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. [9] also examined hip abductor performance during a single-leg squat (Table 11.1). They 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. [37] also investigated the interactions between hip muscle activation and lower extremity joint excursion during a single-leg squat. In contrast to Zeller et al. [57], Nguyen et al. assessed isometric hip extensor and hip abductor strength, as well as gluteus maximus and gluteus medius activity during this test. They reported decreased peak gluteus maximus activity as a predictor of increased hip internal rotation excursion. Conversely, increased peak gluteus maximus activity was a predictor of knee valgus excursion. They surmised that different hip activation strategies may exist for controlling hip motion compared to knee motion. These findings were consistent with Zeller et al. [57] who also reported greater knee valgus range of motion in subjects who generated greater gluteus maximus activity during the single-leg squat.

Interestingly, peak gluteus medius activity was not included in the final predictive models for either increased hip internal rotation excursion or knee valgus excursion. Powers [43] 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 why the final predictive model included gluteus maximus, and not gluteus medius, activity as a predictor of knee valgus.

Regarding associations between strength and muscle activity, Nguyen et al. [37] reported a negative correlation between hip abductor torque and gluteus medius activity ($r = -0.27$; $P = 0.03$), as well as hip extensor torque and gluteus maximus activity ($r = -0.61$; $P < 0.001$). These findings agree with prior works regarding increased neural drive required to complete a functional task in subjects with evident hip weakness [5, 49].

Core Engagement and Lower Extremity Function

To our knowledge, Shirey et al. [46] were the first to examine the influence of volitional core engagement on lower extremity function during a single-leg squat in 14 females. Initially, core strength was determined using methods described by Sahrmann [45] and then, based on subjects' scores, was assigned into either a low or high core strength group. 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. Moreover, subjects with low core strength scores demonstrated less medial-lateral knee stability than those with higher core scores, irrespective of core engagement. Shirey et al. 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.

- An inverse relationship between muscle strength and EMG activity during a single-leg squat reflects an increased neural drive necessary for individuals with less strength.
- Volitional activation of the core musculature may enhance lower extremity function during a single-leg squat.

Gender Differences During a Single-Leg Squat

To date, most studies [8, 11, 12, 14, 18, 24, 26, 29] have examined gender differences during running, cutting, and drop-landing tasks, with limited data available with respect to the single-leg squat test. Sections "Core Strength and Lower Extremity Function" and "Core Neuromuscular Activity and Lower Extremity Function" 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. [57] were the first to specifically examine EMG activity (Table 11.2) and kinematics (Table 11.3) 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 could have stabilized the core to promote controlled lower extremity movement [6, 19]. Zazulak et al. [56] also reported poor trunk neuromuscular control as a predictor of lower extremity injury in the female athlete. A limitation of Zeller et al. 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. [53] 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 et al. [3] found similar gender differences with respect to knee movement during a single-leg squat. As in Willson et al. study [53], 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 section "Core Strength and Lower Extremity Function," Baldon et al. [3] 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.

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 [34, 40].

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 with 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 [9].

As outlined in the beginning of section "Core Neuromuscular Activity and Lower Extremity Function," 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 [43]. This orientation can impart an excessive knee valgus moment, which is a common factor leading to ACL injury in the female athlete [18].

The clinician should assess the female athlete's ability to perform the single-leg squat under controlled, symmetrical, and fatigued states. The effects of fatigue on single-leg squat performance and altered kinematics may not be evident until after repeated exercise. Dierks et al. [10] noted greater correlations between hip abductor strength and peak hip adduction ($r = -0.74$; $P = 0.002$) at the end of a prolonged run in subjects with anterior knee pain. Future studies are required to determine the number of repetitions of a single-leg squat necessary to identify altered hip and knee movement in the fatigue state.

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. 11.5, the athlete is instructed to obtain the plank position and a stick is placed posterior from head to heels. In the example shown in Fig. 11.5, 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

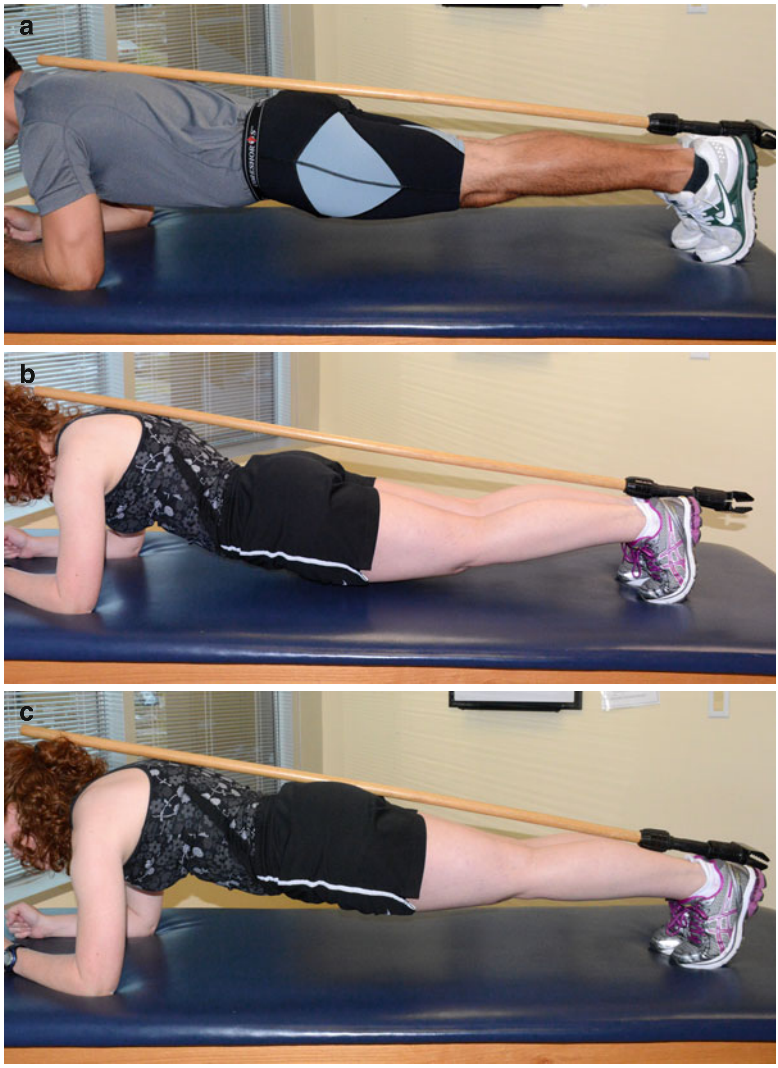


Fig. 11.5 Normal subjects performing the plank test. This test is measured by using a straight stick from the base of the skull to the feet. (**a**) The male has very little lumbar lordosis and an excellent plank position, with a posteriorly rotated pelvis and significantly greater contact with the stick than the female (**b**). (**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

short period of time as shown in the bottom photograph. Correlation of the plank test and 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 11.6 provides a summary of information gained during this screening test.

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.

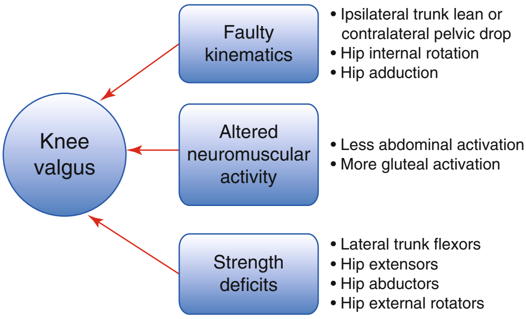


Fig. 11.6 Diagrammatic summary of factors contributing to knee valgus position. The three categories are kinematics, neuromuscular activity, and strength

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 3.0 times more likely than males to incur injury in this manner [44]. 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 important, 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.

References

1. Ageberg E, Bennell KL, Hunt MA et al (2010) Validity and inter-rater reliability of medio-lateral knee motion observed during a single-limb mini squat. BMC Musculoskelet Disord 11:265
2. Alentorn-Geli E, Myer GD, Silvers HJ (2009) Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: mechanisms of injury and underlying risk factors. Knee Surg Sports Traumatol Arthrosc 17(7):705–729
3. Baldon Rde M, Lobato DF, Carvalho LP et al (2011) Relationship between eccentric hip torque and lower-limb kinematics: gender differences. J Appl Biomech 27(3):223–232
4. Berns GS, Hull ML, Patterson HA (1992) Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. J Orthop Res 10(2):167–176
5. Bolgla LA, Malone TR, Umberger BR et al (2011) Comparison of hip and knee strength and neuromuscular activity in subjects with and without patellofemoral pain syndrome. Int J Sports Phys Ther 6(4):285–296
6. Cholewicki J, VanVliet JJ (2002) Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions. Clin Biomech (Bristol, Avon) 17(2):99–105
7. Claiborne TL, Armstrong CW, Gandhi V et al (2006) Relationship between hip and knee strength and knee valgus during a single leg squat. J Appl Biomech 22(1): 41–50
8. Cowley HR, Ford KR, Myer GD et al (2006) Differences in neuromuscular strategies between landing and cutting tasks in female basketball and soccer athletes. J Athl Train 41(1):67–73
9. Crossley KM, Zhang WJ, Schache AG et al (2011) Performance on the single-Leg squat task indicates Hip abductor muscle function. Am J Sports Med 39(4):866–873
10. Dierks TA, Manal KT, Hamill J et al (2008) Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. J Orthop Sports Phys Ther 38(8):448–456
11. Earl JE, Monteiro SK, Snyder KR (2007) Differences in lower extremity kinematics between a bilateral drop-vertical jump and a single-leg step-down. J Orthop Sports Phys Ther 37(5):245–252
12. Ferber R, Davis IM 3rd, Williams DS (2003) Gender differences in lower extremity mechanics during running. Clin Biomech (Bristol, Avon) 18(4):350–357
13. Ford KR, Myer GD, Toms HE et al (2005) Gender differences in the kinematics of unanticipated cutting in young athletes. Med Sci Sports Exerc 37(1): 124–129

14. Ford KR, Myer GD, Smith RL (2006) A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. Clin Biomech (Bristol, Avon) 21(1):33–40
15. Fung DT, Zhang LQ (2003) Modeling of ACL impingement against the intercondylar notch. Clin Biomech (Bristol, Avon) 18(10):933–941
16. Geiser CF, O'Connor KM, Earl JE (2010) Effects of isolated hip abductor fatigue on frontal plane knee mechanics. Med Sci Sports Exerc 42(3):535–545
17. Gilchrist J, Mandelbaum BR, Melancon H et al (2008) A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. Am J Sports Med 36(8):1476–1483
18. Hewett TE, Myer GD, Ford KR et al (2005) Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med 33(4):492–501
19. Hodges PW, Richardson CA (132) Contraction of the abdominal muscles associated with movement of the lower limb. Phys Ther 77(2):132–142; discussion 142–134
20. Ireland ML (2002) The female ACL: why is it more prone to injury? Orthop Clin North Am 33(4):637–651
21. Jacobs CA, Uhl TL, Mattacola CG et al (2007) Hip abductor function and lower extremity landing kinematics: sex differences. J Athl Train 42(1):76–83
22. Kernozek TW, Torry MR, Iwasaki M (2008) Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. Am J Sports Med 36(3):554–565
23. Krosshaug T, Nakamae A, Boden BP et al (2007) Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. Am J Sports Med 35(3):359–367
24. Lawrence RK 3rd, Kernozek TW, Miller EJ et al (2008) Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. Clin Biomech (Bristol, Avon) 23(6):806–813
25. Leetun DT, Ireland ML, Willson JD et al (2004) Core stability measures as risk factors for lower extremity injury in athletes. Med Sci Sports Exerc 36(6): 926–934
26. Lephart SM, Ferris CM, Riemann BL et al (2002) Gender differences in strength and lower extremity kinematics during landing. Clin Orthop 401:162–169
27. Li RT, Lorenz S, Xu Y et al (2011) Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. Am J Sports Med 39(12):2595–2603
28. Lubowitz JH, Appleby D (2011) Cost-effectiveness analysis of the most common orthopaedic surgery procedures: knee arthroscopy and knee anterior cruciate ligament reconstruction. Arthroscopy 27(10): 1317–1322
29. Malinzak RA, Colby SM, Kirkendall DT (2001) A comparison of knee joint motion patterns between men and women in selected athletic tasks. Clin Biomech (Bristol, Avon) 16(5):438–445
30. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010
31. Markolf KL, Burchfield DM, Shapiro MM et al (1995) Combined knee loading states that generate high anterior cruciate ligament forces. J Orthop Res 13(6):930–935
32. McLean SG, Walker K, Ford KR et al (2005) Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. Br J Sports Med 39(6):355–362
33. Munro A, Herrington L, Carolan M (2012) Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. J Sport Rehabil 21(1):7–11
34. Myer GD, Chu DA, Brent JL et al (2008) Trunk and hip control neuromuscular training for the prevention of knee joint injury. Clin Sports Med 27(3):425–448; ix
35. Nagano Y, Ida H, Akai M et al (2007) Gender differences in knee kinematics and muscle activity during single limb drop landing. Knee 14(3):218–223
36. Neumann DA (2010) Kinesiology of the musculoskeletal system, 2nd edn. Mosby, St. Louis
37. Nguyen AD, Shultz SJ, Schmitz RJ et al (2011) A preliminary multifactorial approach describing the relationships among lower extremity alignment, hip muscle activation, and lower extremity joint excursion. J Athl Train 46(3):246–256
38. Panjabi MM (1992) The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. J Spinal Disord 5(4):383–389; discussion 397
39. Patrek MF, Kernozek TW, Willson JD et al (2011) Hip-abductor fatigue and single-leg landing mechanics in women athletes. J Athl Train 46(1):31–42
40. Pollard CD, Sigward SM, Ota S et al (2006) The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. Clin J Sport Med 16(3):223–227
41. Pope MH, Panjabi M (1985) Biomechanical definitions of spinal instability. Spine (Phila Pa 1976) 10(3):255–256
42. Portney LG, Watkins MP (2009) Foundations of clinical research. Applications to practice, 3rd edn. Prentice Hall Health, Upper Saddle River
43. Powers CM (2010) The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. J Orthop Sports Phys Ther 40(2):42–51
44. Prodromos CC, Han Y, Rogowski J et al (2007) A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. Arthroscopy 23(12): 1320–1325, e1326
45. Sahrmann S (2002) Diagnosis and treatment of movement impairment syndromes. Mosby, Philadelphia
46. Shirey M, Hurlbutt M, Johansen N et al (2012) The influence of core musculature engagement on hip and knee kinematics in women during a single leg squat. Int J Sports Phys Ther 7(1):1–12

47. Shultz SJ, Schmitz RJ, Nguyen AD et al (2010) ACL research retreat V: an update on ACL injury risk and prevention, March 25–27, 2010, Greensboro, NC. J Athl Train 45(5):499–508
48. Silvers HJ, Mandelbaum BR (2007) Prevention of anterior cruciate ligament injury in the female athlete. Br J Sports Med 41(Suppl 1):i52–i59
49. Souza RB, Powers CM (2009) Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. J Orthop Sports Phys Ther 39(1):12–19
50. Souza RB, Powers CM (2009) Predictors of hip internal rotation during running: an evaluation of hip strength and femoral structure in women with and without patellofemoral pain. Am J Sports Med 37(3): 579–587
51. van der Hart CP, van den Bekerom MP, Patt TW (2008) The occurrence of osteoarthritis at a minimum of ten years after reconstruction of the anterior cruciate ligament. J Orthop Surg Res 3:24
52. Willson JD, Dougherty CP, Ireland ML et al (2005) Core stability and its relationship to lower extremity function and injury. J Am Acad Orthop Surg 13(5): 316–325
53. Willson JD, Ireland ML, Davis I (2006) Core strength and lower extremity alignment during single leg squats. Med Sci Sports Exerc 38(5): 945–952
54. Willson JD, Davis IS (2008) Utility of the frontal plane projection angle in females with patellofemoral pain. J Orthop Sports Phys Ther 38(10):606–615
55. Willy RW, Davis IS (2011) The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. J Orthop Sports Phys Ther 41(9):625–632
56. Zazulak BT, Hewett TE, Reeves NP et al (2007) Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. Am J Sports Med 35(7): 1123–1130
57. Zeller BL, McCrory JL, Kibler WB et al (2003) Differences in kinematics and electromyographic activity between men and women during the single-legged squat. Am J Sports Med 31(3):449–456

Gender Effect of Fatigue on Lower Extremity Kinematics and Kinetics During Athletic Tasks

12

James Onate and Nelson Cortes

Contents

J. Onate, Ph.D., A.T.C., F.N.A.T.A. (✉)
School of Health and Rehabilitation Sciences, Ohio State University, 228C Atwell Hall, 453 West 10th Ave, Columbus, OH 43210, USA
e-mail: jimmy.onate@osumc.edu

N. Cortes, Ph.D.
Sports Medicine Assessment, Research & Testing (SMART) Laboratory, George Mason University, Prince William Campus, Bull Run Hall 208B, 10900 University Blvd, MS 4E5, Manassas, VA 20110, USA
e-mail: ncortes@gmu.edu

Overview of Fatigue and ACL Injury

The role of fatigue potentially contributing to anterior cruciate ligament (ACL) injuries has been discussed in the literature by numerous researchers [3, 5, 7, 8, 16, 24, 26, 36, 38]. Fatigue may be generally defined as a decrease in force production or an inability to regenerate the original force in the presence of an increased perception of effort [11]. The goal of this chapter is to examine the role of generalized whole-body central fatigue versus isolated muscular peripheral fatigue, report the epidemiological evidence relative to fatigue and ACL injury occurrence, understand the influence of different types of fatigue protocols on biomechanical movement patterns, and evaluate gender differences in biomechanical movement patterns under fatigued conditions.

Central and Peripheral Fatigue Effects on Movement Biomechanics

Studies evaluating the effects of fatigue on movement biomechanics may be broken down into two separate types, central and peripheral. Central fatigue represents a reduction in neural drive or motor command to the muscle, resulting in a decline in force production or tension development [9]. Central fatigue encompasses changes at any or all sites in the pathway from the motor cortex to the neuromuscular junction [11]. A subset of central fatigue, supraspinal fatigue, refers to the failure to generate maximal output from the motor

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_12,

cortex. Gandevia et al. [10] examined the effects of transcranial magnetic stimulation of the motor cortex during a maximal voluntary contraction. These investigators found that motor cortex stimulation resulted in a superimposed twitch, indicating that even at maximal voluntary contraction, motor cortical output was not optimal.

McLean and colleagues have led the charge in investigating the role of central fatigue on promotion of high-risk biomechanics [28, 29]. One of the initial studies focused on gender differences using a generalized lower limb fatigue protocol [28]. Following a drop-jump task, fatigue increased initial and peak knee internal rotation and abduction moments, with females having more pronounced increases following the fatigue protocol. McLean and Samorezov [29] continued to explore the relationship of fatigue and its effects on landing biomechanics by examining a fatigue protocol of repetitive single-leg squats until failure and randomly ordered unilateral and bilateral landings in 20 female collegiate athletes. Fatigue produced a significant decrease in initial contact knee flexion angle and peak stance knee flexion moment. Additionally, significant increases in peak stance hip internal rotation angles and knee abduction angles and loads were observed. The authors concluded that unilateral fatigue induces a fatigue crossover to the contralateral limb during single-leg landings, thereby supporting the theory that a central fatigue process influences poor biomechanical movement patterns.

In further support of the central fatigue theory contributing to altered biomechanical movement patterns, Pappas et al. [34] conducted a study on 32 recreational athletes who performed bilateral drop landings from a 40-cm height. Kinematic, kinetic, and electromyographic (EMG) data showed that fatigue increased peak foot abduction by 1.7° ($P=0.042$), peak rectus femoris activity by 27 % ($P=0.018$), and peak vertical ground reaction force by 20 % ($P=0.038$). Interestingly, these investigators did not observe knee frontal plane motion changes following fatigue. These findings limit the central fatigue hypothesis relative to a key biomechanical motion pattern as a potential predictor of ACL injury risk.

An investigation from the authors' laboratory [36] that assessed a functional short-term fatigue protocol on lower extremity biomechanics provided further information relative to the central fatigue theory influencing movement patterns. Fifteen female collegiate soccer athletes demonstrated a significant group change from pre-fatigue to post-fatigue conditions for increased knee internal rotation (pre = 7.9 ± 6.5° and post = 11.4 ± 7.5°, $P=0.011$), decreased knee flexion angle (pre = −40.0 ± 6.3° and post = −36.6 ± 6.2°, $P=0.003$), and reduced hip flexion angles (pre = 43.2 ± 9.5° and post = 35.5 ± 8.7°, $P=0.002$). Participants presented a more extended and internally rotated position at the knee post-fatigue, which may increase their susceptibility for ACL tears.

In addition to functional and general fatigue laboratory-based protocols demonstrating biomechanical patterns associated with increased ACL injury risk, Zebis et al. [44] reported the effects of muscle fatigue following a simulated handball match on neuromuscular strategies during a functional side-cutting movement task. The EMG activity of the quadriceps and hamstrings of 14 female team handball players was assessed pre- and post-fatigue game simulation. Maximal isometric voluntary contraction strength for both the quadriceps and hamstring muscles was significantly decreased following simulated game fatigue. In addition, a selective decrease in hamstring activity was observed during the side-cutting movement task. Thus, the recommendation was made that screening procedures aimed at functional movements to reveal specific fatigue-induced deficits in ACL-agonist muscle activation (i.e., hamstrings) should be conducted. While whole-body, general lower extremity, and functional sport-simulated protocols have demonstrated that a central fatigue concept may contribute to poor movement biomechanics (lending theoretically to the role of fatigue in ACL injury), caution must be applied. Further prospective epidemiological data are required to support these laboratory-based biomechanical-central fatigue-related theories to actual ACL injury risk.

Peripheral fatigue represents a decrease in the capability of the skeletal muscle to generate force production because of action potential failure, excitation-contraction coupling failure, or impairment of cross-bridge cycle in the presence of unchanged or increasing neural drive [17]. Peripheral fatigue is a decrease in the muscle's ability to generate force, which occurs at or distal to the neuromuscular junction [11]. Thomas et al. [39] evaluated the effects of isolated fatigue of the quadriceps and hamstrings (QH) muscles on lower extremity biomechanics during a dynamic single-leg forward hop. Isolated fatigue of the QH muscles was induced through sets of alternating QH concentric contractions on an isokinetic dynamometer. QH fatigue produced significant increases in initial contact (IC) hip internal rotation and knee extension and external rotation angles, with the increases in knee extension and external rotation being maintained at the time of peak vertical ground reaction force (vGRF). Gender differences were noted, with females landing with greater hip flexion and less abduction than males at both IC and peak vGRF as well as greater knee flexion at peak vGRF.

In a separate study, Thomas et al. [40] investigated the effects of isolated hip and ankle fatigue on landing biomechanical strategies in a group of 16 healthy collegiate females. An isolated muscle movement task for hip rotator and triceps surae fatigue was conducted, with fatigue defined as an 80 % decrease in peak torque from baseline. Hip rotator fatigue increased initial contact and peak stance hip internal rotation angles, yet did not produce any other significant knee or hip frontal and sagittal plane movement alterations. The triceps surae fatigue resulted in decreased initial contact knee flexion, which may be reflective of a potential modification following fatigue that can be reflective of increased ACL injury risk movement pattern. These investigations reported that overall movement strategy changes following isolated hip and ankle musculature created at-risk movement modifications.

Gehring et al. [12] evaluated the effects of isolated closed kinetic chain exercise on two-legged landings in 13 females and 13 males. The isolated peripheral fatigue protocol resulted in significantly reduced preactivation of the medial and lateral hamstrings as well as the gastrocnemius muscles. These investigators concluded that isolated peripheral fatigue is associated with altered muscle activation patterns, but a lack of significant kinematic and kinetic changes in their results limits the implications of isolated peripheral fatigue role in altering biomechanical movement patterns.

Critical Points

- Central fatigue results in altered biomechanical movement patterns that are theorized to be associated with increased ACL injury risk.
- Peripheral isolated joint fatigue results have been mixed in altering biomechanical movement patterns.
- Currently, no prospective epidemiological studies assessing central or peripheral fatigue on ACL injury risk have been conducted, thus limiting the findings of central and peripheral fatigue to biomechanical laboratory studies.

Epidemiological Considerations of Fatigue and ACL Injury

Fatigue has been considered to be an extrinsic risk factor affecting the neuromusculoskeletal system, and its association with decreased movement control and increased joint laxity potentially contributes to ACL injury occurrence. This association has been made from the occurrence of severe knee injuries, specifically ACL injuries, that tend to happen toward the end of a soccer game or practice [33]. Neuromuscular fatigue is a natural occurrence in physical activity participation and has been theoretically implicated in noncontact ACL injury rates [7, 28]. Neuromuscular fatigue has been shown to negatively affect knee motions and loads, causing altered landing characteristics consistent with noncontact ACL injury mechanisms [24, 28]. However, the epidemiological data inferring increased risk as athletes succumb to the physiological demands of intense activity [6, 18] as being directly attributable to increased ACL injury risk is lacking.

Hawkins et al. [19] evaluated injuries in English professional football (soccer) players over two competitive seasons. A total of 6,030 injuries were reported, with an average of 1.3 injuries per player per season. The lower extremity (87 %) was the most common site for injury occurrence, with the knee accounting for 17 % of these injuries. Competition injuries represented 63 % of those reported, with a significant ($P<0.01$) amount of injuries occurring toward the ends of both halves of play. Liederbach et al. [25] prospectively investigated the incidence of ACL injuries among elite level ballet and modern dancers over a 5-year period. Of 298 dancers, 12 reported ACL injuries resulting in an incidence rate of 0.009 per 1,000 exposures. Closer inspection of the women dancers revealed that women modern dancers experienced an ACL injury rate of 0.015 per 1,000 exposures and women ballet dancers had even a smaller rate of 0.0005 per 1,000 exposures. Even though these incident rates are exceedingly low for an ACL injury as compared to soccer or basketball, the majority of the ACL injury injuries occurred late during the day and later in the season, thus the authors postulated that fatigue may be a contributing factor. Yet, subjective self-report or objective physiological measurements of fatigue were not documented, and therefore, the association of ACL injury and fatigue is mainly conjecture. This information has been subsequently cited [28] as potentially linking fatigued states with increased ACL injury occurrence, which cannot be directly based on the study's findings. Clinically, one may assume that individuals are more fatigued at the ends of halves of play, end of the day, and latter aspects of the season, yet a direct link to fatigued states and ACL injury has not been empirically completed.

Critical Points

- Theoretical associations of ACL injury and fatigue levels have been presented in the literature, but epidemiological studies to directly ascertain this association are lacking.
- Few epidemiological studies are available that directly evaluate fatigue levels and its association with ACL injury occurrence.
- Future studies are needed to correlate fatigue state with ACL injury occurrence utilizing objective and subjective information at the time of injury.

Fatigue Protocols Influence Kinematic and Kinetic Patterns

Specifically, fatigue has been shown to alter various biomechanical parameters including increased peak proximal tibial anterior shear force [7], increased knee abduction and knee internal rotation moments [28, 29], decreased knee flexion angle [7, 29], and increased hip internal rotation moments [29]. When comparing genders across fatigued states, females have increased hip flexion, larger peak valgus angle and maximum knee valgus angle, decreased knee flexion, greater knee extension moment, and higher peak proximal tibial anterior shear force [7, 24, 28].

The effect of fatigue on the joint position of the knee has been controversial. One study that assessed side-step cutting maneuvers reported no differences between knee kinetics and kinematics after a fatigue protocol (60-min shuttle run) (Fig. 12.1) [38]. However, fatigue caused significant increases in hip extension and internal rotation, peak stance knee abduction and internal rotation, and ankle supination angles at initial contact (Fig. 12.2) [5].

Chappell et al. [7] concluded that fatigue altered motor control strategies, possibly leading to increases in anterior tibial shear force, strain on the ACL, and risk of injury in male and female recreational athletes. In this study, the subjects

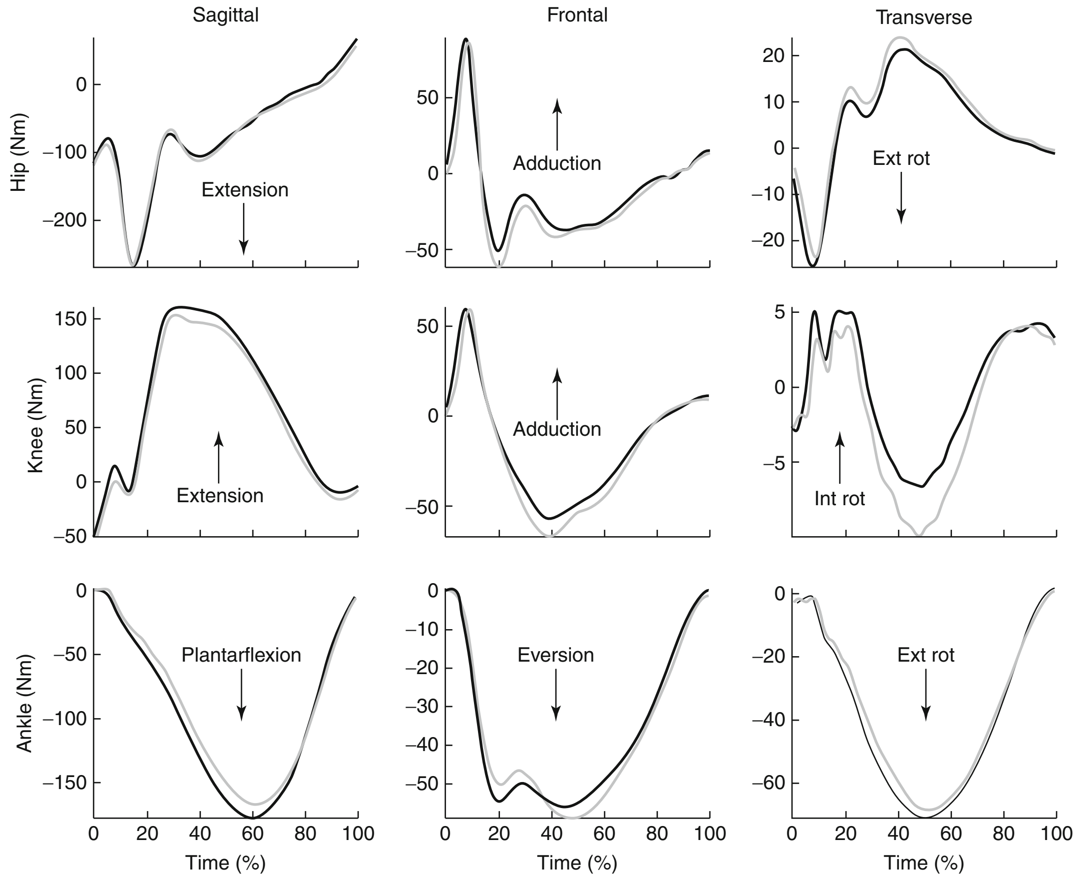


Fig. 12.1 Group mean pre- (*black*) and post- (*gray*) ISR hip, knee, and ankle moments during stance for each plane (Reprinted with permission from Sanna [38])

performed a fatigue protocol involving a series of unlimited sets of five consecutive vertical jumps followed by a 30-m sprint. Wojtys et al. [42] also found that fatigue altered the neuromuscular response to anterior tibial translation, affecting the dynamic stability of the knee. This study reported a 32 % increase in anterior tibial translation after fatigue. Rozzi et al. [37] concluded that muscular fatigue alters the ability to sense joint motion in soccer and basketball players. Since deficits in the ability to sense joint motion may reflect the ability to respond to joint forces, there may be an increased risk of ligament injury in these individuals.

Short-term anaerobic fatigue protocols, as well as long-term aerobic whole-body fatigue protocols, have been conducted to evaluate movement biomechanics associated with increased risk of ACL injury [8, 26, 36]. Fatigue has been induced through single-leg squats, consecutive repetitions of vertical jumps and short sprints, and maximum repetitions on a leg-press machine. Conflicting approaches have been implemented regarding fatigue protocols, without a consensus on what type of protocol is more applicable to assess individuals with faulty biomechanical movement patterns. Studies have reported the need for sport-specific fatigue protocols that mimic sporting demands placed on the individual, yet minimal research comparing the effects of functional sport-specific fatigue on lower extremity joint kinematics and kinetics is available. Soccer-specific fatigue protocols have recently been created to assess the particular

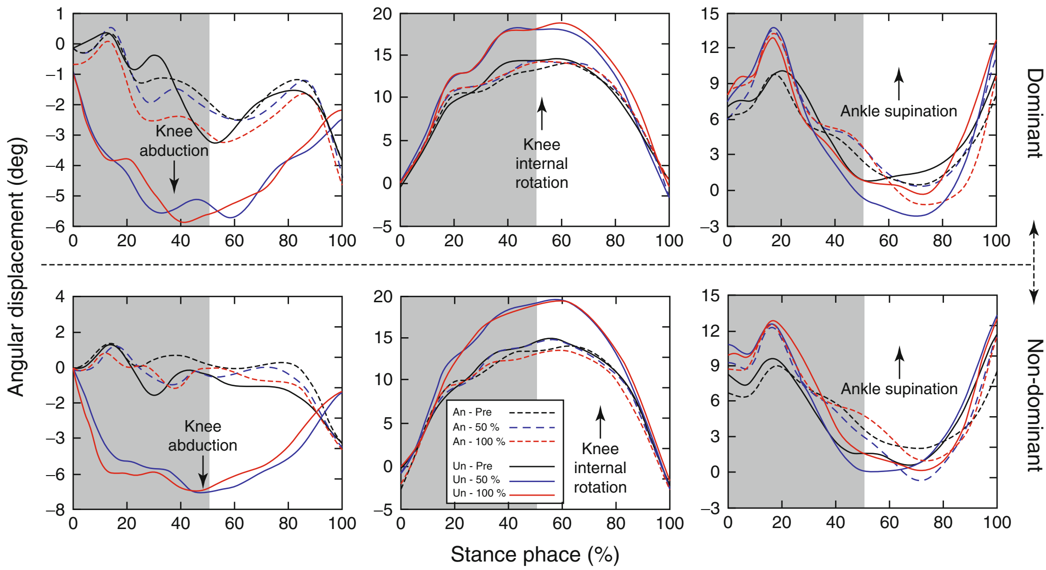


Fig. 12.2 Statistically significant ($P<0.006$) interactions between the main effects of movement and fatigue conditions were observed for peak stance phase (0–50 %) hip internal rotation and knee abduction measures. Specifically in both cases, fatigue effects were more pronounced during unanticipated compared to anticipated landings (Reprinted with permission from Borotikar et al. [5])

demands of this activity in order to analyze the neuromuscular changes that occur during fatigued states in this sport [8, 13–15, 26, 36, 38]. Lucci et al. [26] and Quammen et al. [36] developed two soccer-specific fatigue protocols aimed at addressing the effects of fatigue on lower extremity biomechanical patterns.

Functional Agility Short-Term Fatigue Protocol (FAST-FP)

The functional agility short-term fatigue protocol (FAST-FP) was developed to address the need to mimic soccer-related tasks while fatiguing the athletes at high intensity [26, 36]. The FAST-FP protocol begins with the athlete performing a series of step-up and step-down movements onto and off of a 30-cm-high box for 20 s in time with a metronome set to 220 beats/min. Immediately after, the athlete performs one repetition of an L drill among three cones.

The L drill protocol is as follows. The athlete begins in a three-point stance in front of three cones that are arranged in the shape of an “L” and spaced 4.05 m apart. Starting at the first cone, the athlete sprints to the second cone, sprints back to the first cone, runs back to the second cone, and runs around the right side of the second cone to the third cone. Then, the athlete runs in a circle around the third cone from the inside to the outside, sprints back to the second cone, runs around the left side of the second cone, and runs back to the first cone (Fig. 12.3).

After completing the L drill, the athlete performs five consecutive countermovement jumps, staying within 80 % (± 2 %) of their maximal vertical jump. After the vertical jumps, the athlete runs down and back on an agility ladder. When completing the protocol for the first and third times, the athlete runs forward on the agility ladder drill, ensuring that both feet touch inside each space of the ladder. When completing the protocol for the second and fourth times, the athlete runs sideways on the ladder. The ladder drill is performed with the rhythm of a metronome set at 220 beats/min to maintain a high intensity of the protocol. Completing the four tasks (step-up and step-down movements, L drill, vertical jumps, and ladder drill) counts as one set of the protocol. The athlete performs four sets of the protocols, with no rest between sets.

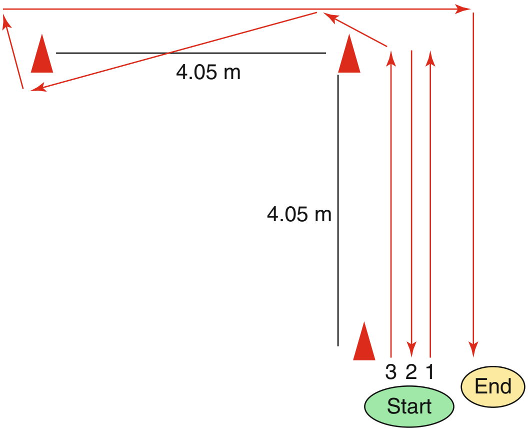


Fig. 12.3 Schematic of the L drill portion of the functional agility short-term fatigue protocol. The athlete begins at the first (*bottom*) cone (#1), runs to the second (*top right*) cone, turns and sprints back to the first cone, and then follows the numbers and arrows through the course (Reprinted with permission from Quammen et al. [36])

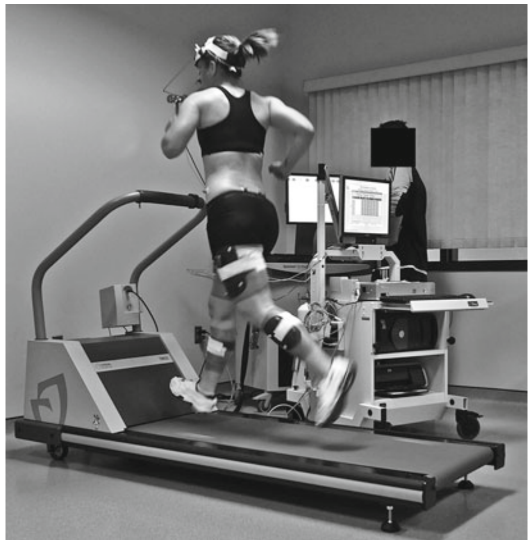


Fig. 12.4 A maximum oxygen consumption test was conducted before the 30-min running protocol for the slow linear oxidative fatigue protocol (Reprinted with permission from Quammen et al. [36])

Slow Linear Oxidative Fatigue Protocol (SLO-FP)

The slow linear oxidative fatigue protocol (SLO-FP) was developed with the primary goal to stimulate fatigue from a cardiovascular perspective, which would allow replicating the cardiovascular demands that soccer athletes experience during a match [26, 36]. This protocol begins with the athlete performing a maximal oxygen uptake (VO_2max) test. The protocol for the VO_2max test is based on previous research and required the participant to run at 9 km/h for 5 min, followed by 1-km/h speed increments every 2 min until exhaustion (Fig. 12.4). An athlete reached maximal fatigue if two of the following criteria were met: (1) heart rate reached 90 % of age-calculated maximum heart rate, (2) respiratory quotient greater than 1.1, (3) reached a plateau in the VO_2max curve, and (4) unable to continue running. The treadmill gradient is kept at 0° for the entire VO_2max test. After completing the VO_2max test, the athlete rests for a maximum of 5 min. Immediately after the resting period, the athlete steps back onto the treadmill and alternates between two running speeds throughout a 30-min treadmill run. Six intervals are conducted that consist of running at a speed of 70 % of the final VO_2max speed for 4 min, followed by running at a speed of 90 % of the final VO_2max speed for 1 min. This represents moderate jogging (70 % of maximum speed) and sprinting (90 % of maximum speed).

Comparison of SLO-FP and FAST-FP on Lower Extremity Biomechanics While Performing Two Athletic Tasks

Recently, Lucci et al. [26] investigated the effects of the FAST-FP and SLO-FP in lower extremity biomechanics while performing a side-step cutting task. The authors found no differences between the SLO-FP and FAST-FP in lower extremity biomechanics. These investigators reported that the athletes had decreased hip flexion and increased hip internal rotation, as well as decreased knee flexion and decreased knee internal rotation regardless of the protocol used (Table 12.1). They suggested that fatigue experiments may use protocols similar to the FAST-FP because they alter lower extremity biomechanics in a similar manner as the longer protocol. However, there were limitations with their

Table 12.1 Descriptive statistics for kinematic variables between two fatigue protocols at initial contact, peak vertical ground reaction force, peak posterior ground reaction force, peak knee flexion, and peak stance[a]

Kinematic variable	Slow linear oxidative fatigue protocol						Functional agility short-term fatigue protocol					
	Pretest			Posttest			Pretest			Posttest		
	Mean	SD	95 % CI	Mean	SD	95 % CI	Mean	SD	95 % CI	Mean	SD	95 % CI
Initial contact												
Knee flexion (−)/ extension (+)	−25.8	5.7	−28.9, −22.6	−22.6	9.7	−28.0, −17.3	−25.5	8.0	−29.9, −21.1	−22.3	7.1	−26.2, −18.3
Knee abduction (−)/adduction (+)	−1.1	3.0	−2.7, 0.6	−1.9	2.8	−3.4, −0.3	−2.0	2.5	−3.4, −0.6	−2.4	3.7	−4.4, −0.4
Knee external (−)/internal (+) rotation	7.6	6.3	4.1, 11.1	8.4	4.5	5.9, 10.9	14.2	6.2	4.7, 11.2	10.9	5.6	7.8, 14.0
Hip flexion (+)/ extension (−)	36.2	8.7	31.4, 41.1	32.6	9.3	27.5, 37.7	36.5	8.0	32.1, 41.0	28.1	9.3	23.0, 33.3
Hip external (−)/ internal (+) rotation	13.2	9.4	7.9, 18.4	10.1	8.3	4.3, 15.9	9.7	6.6	6.0, 13.4	5.7	9.4	0.4, 10.9
Peak vertical ground reaction force												
Knee flexion (−)/ extension (+)	−41.9	8.2	−46.4, −37.3	−40.1	7.3	−44.1, −36.1	−41.6	7.7	−45.9, −37.3	−37.4	6.8	−41.2, −33.6
Knee abduction (−)/adduction (+)	−2.0	5.3	−4.9, 1.0	−3.0	5.3	−5.9, 0	−3.7	4.0	−5.9, −1.5	−3.4	6.2	−6.8, 0.0
Knee external (−)/internal (+) rotation	14.1	6.0	10.8, 17.4	14.7	4.7	12.3, 17.3	14.2	6.2	10.8, 17.6	17.5	5.6	14.4
Hip flexion (+)/ extension (−)	31.8	10.6	25.9, 37.6	28.0	10.8	22.1, 34.0	32.1	9.0	27.1, 37.1	23.2	10.9	17.2, 29.3
Hip external (−)/ internal (+) rotation	7.8	9.4	2.7, 13.0	3.8	10.9	−2.2, 9.8	4.4	7.5	0.2, 8.5	0.3	8.9	−4.6, 5.3
Peak posterior ground reaction force												
Knee flexion (−)/ extension (+)	−36.8	5.0	−39.6, −34.1	−36.2	8.2	−40.7, −31.6	−34.2	8.6	−39.0, −29.5	−31.2	7.7	−35.5, −26.9

Knee external (−)/internal (+) rotation	12.8	5.9	9.5, 16.0	14.1	5.2	11.2, 17.0	11.4	5.2	8.6, 14.3	15.1	4.8	12.4, 17.7
Hip flexion (+)/ extension (−)	35.2	8.8	30.3, 30.0	31.0	9.4	25.8, 36.2	35.6	8.2	31.1, 40.2	26.5	9.8	21.1, 31.9
Hip external (−)/ internal (+) rotation	10.5	9.5	5.2, 15.8	6.2	10.5	0.4, 12.0	8.2	6.5	4.6, 11.8	3.1	9.1	−1.9, 8.1
Peak knee flexion												
Knee flexion (−)/ extension (+)	−54.53	5.14	−57.4, −51.7	−51.19	6.38	−54.6, −47.6	−53.07	7.04	−57.0, −49.2	−48.28	7.36	−52.4, −44.2
Knee abduction (−)/adduction (+)	−3.45	6.2	−6.9, 0.0	−4.60	6.3	−8.1, −1.1	−6.10	5.33	−9.0, −3.1	−5.58	7.63	−9.8, 1.4
Knee external (−)/internal (+) rotation	16.59	6.33	13.1, 20.1	17.36	5.67	14.2, 20.5	17.22	6.64	13.5, 20.9	19.80	6.32	16.3, 23.3
Peak stance												
Hip flexion (+)/ extension (−)	38.19	9.18	33.1, 43.3	33.89	9.49	28.6, 39.1	38.31	8.81	33.4, 43.2	29.34	9.73	24.0, 34.7
Hip external (−)/ internal (+) rotation	3.14	9.92	−2.4, 8.6	−0.75	11.35	−7.0, 5.5	−0.48	7.60	−4.7, 3.7	−4.46	8.16	−9.0, 0.1
Knee abduction (−)/adduction (+)	−5.44	5.20	−8.3, −2.6	−6.23	5.00	−9.0, −3.5	−7.11	4.80	−9.8, −4.5	−7.18	6.36	−10.7, −3.7

Data from Lucci et al. [26]

[a]All variables measured in degrees. *95 % CI* 95 % confidence interval

study that are interesting to note. Specifically, athletes had similar heart rates at the end of each protocol, which suggests that the pattern of fatigue was not similar to a soccer match. While the athletes met the criteria defined by the research group, they were not able to objectively quantify the level of fatigue, suggesting that objective measures and scales of effort should be used.

Similarly to the previous study, Quammen et al. [36] evaluated the effects of two fatigue protocols (SLO-FP, FAST-FP) on lower extremity biomechanics during an unanticipated running-stop-jump task in female National Collegiate Athletic Association Division I soccer players. These authors found similar effects on lower extremity biomechanics, regardless of the protocol. A decrease in knee and hip flexion was observed regardless of the protocol used. The authors reported that, while the SLO-FP and FAST-FP were based on previous research, they presented unique characteristics not previously implemented. Specifically, the FAST-FP included the L and agility ladder drills that were not used previously but are commonly used during practices for soccer. Quammen and colleagues [36] suggested that while the differences between the two fatigue protocols were minimal, they found that the FAST-FP augmented changes in frontal plane hip and knee biomechanics compared with the SLO-FP. During the FAST-FP, hip abduction was greater than during the SLO-FP. They suggested that the multidirectional movements associated with the FAST-FP solicit the hip musculature more than the SLO-FP, resulting in greater hip abduction. Contrastingly, the SLO-FP primarily affected the hip flexors and extensors (Table 12.2). The investigators suggested that ACL injury prevention programs should be tailored to the type of practice that will occur (e.g., moderate to high intensity) because during the FAST-FP, altered lower extremity biomechanics were observed as early as 5 min. Within this short period of time, several movement patterns were altered due to the high demands of the protocol. In particular, increased hip abduction, internal rotation, and internal knee adduction moment were noted. Further, valid screening tools should be used to access injury risk during a fatigued state. As an example, the Landing Error Scoring System that has shown criterion validity and interrater reliability [32] may be used and investigated for its ability to determine altered movement patterns during a fatigued status. This screening instrument is inexpensive and would create an efficient process to determine risk factors associated with fatigue conditions that can be used on the field rather than in a laboratory setting.

Critical Points

- A 5-min FAST-FP produces similar changes than a 45-min SLO-FP.
- Both fatigue protocols altered lower extremity biomechanics, placing athletes at a higher risk for injury.
- Further studies are needed to address the lack of objective measures to determine the status of fatigue during various experiments.
- If epidemiological studies objectively demonstrate that fatigue is a key concern when injury occurs, screening tools should be implemented to determine athletes that may have higher risk of injury when they are fatigued.

Biomechanical Gender Differences Following Fatigue

Gender differences in ACL injury occurrence [1, 2, 22, 23, 30, 31, 41] and movement biomechanics [4, 16, 20, 21, 24, 27, 28, 35, 37, 43] have been presented throughout the literature. Additionally, the effect of fatigue on biomechanical movement patterns has been demonstrated repeatedly. Thomas et al. [39] reported gender differences during single-leg landing tasks following isolated QH muscle fatigue protocols. Females landed with significantly greater hip flexion and less abduction than males at both IC and peak vGRF and as well had greater knee flexion at peak vGRF. Additionally, the peak vGRF was larger for

Table 12.2 Descriptive statistics for kinematic variables between two fatigue protocols at initial contact, peak vertical ground reaction force, peak posterior ground reaction force, peak knee flexion, and peak stance[a]

	Slow linear oxidative fatigue protocol				Functional agility short-term fatigue protocol			
	Pretest		Posttest		Pretest		Posttest	
Kinematic variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Initial contact								
Knee flexion (–)/extension (+)	–27.4	8.5	–24.5	9.2	–25.9	8.1	–25.2	9.1
Knee abduction (–)/adduction (+)	–0.9	3.2	–1.0	3.9	–1.3	4.2	–2.3	5.6
Knee internal (+)/external (–) rotation	8.8	7.3	8.8	6.5	7.9	7.8	11.9	9.8
Hip flexion	50.3	10.5	46.5	6.6	49.9	8.4	42.9	9.6
Hip abduction (–)/adduction (+)	–5.0	5.2	–5.6	4.6	–5.5	4.5	–6.4	5.8
Peak vertical ground reaction force								
Knee flexion (–)/extension (+)	–39.1	5.1	–36.1	7.4	–38.4	5.0	–35.7	5.6
Hip flexion	50.4	11.5	46.9	7.3	50.5	9.1	42.5	9.5
Peak posterior ground reaction force								
Knee flexion (–)/extension (+)	–38.3	5.7	–36.6	7.8	–38.5	5.5	–34.9	6.7
Knee abduction (–)/adduction (+)	–0.4	4.7	–1.1	5.2	–1.8	5.1	–2.5	6.6
Hip flexion	51.3	12.0	46.9	7.3	50.8	9.5	43.4	9.9
Peak knee flexion								
Knee flexion (–)/extension (+)	–55.9	7.8	–53.3	5.6	–57.61	8.9	–51.6	10.1
Knee abduction (–)/adduction (+)	–2.4	5.9	–3.7	6.2	–5.2	5.3	–5.6	6.4
Hip flexion	44.6	12.8	40.5	7.6	45.6	10.4	36.8	9.7
Hip abduction (–)/adduction (+)	–1.8	4.1	–1.9	3.7	–3.1	4.6	–4.4	4.7
Peak stance								
Knee abduction (–)/adduction (+)	–4.6	3.9	–5.5	5.1	–6.1	4.9	–7.0	5.9
Hip flexion	53.3	11.9	49.1	6.7	53.3	10.0	45.6	9.8

Data from Quammen et al. [36]

[a]All variables measured in degrees

females than males. Kernozek et al. [24] found significant biomechanical landing pattern differences following a fatigue protocol of parallel squat exercises to failure. Neuromuscular fatigue caused both men and women to land with greater amounts of hip flexion ($P = 0.012$) as compared to the baseline pre-fatigue state. Males exhibited greater peak knee flexion angles post-fatigue compared to females, thus indicating they used a knee squatting strategy to help control the landing and dissipate the forces imposed following the fatigue protocols. Females demonstrated larger peak knee valgus angles overall, but a fatigue-gender interaction was not significant ($P = 0.153$), thus indicating that peak knee valgus angles were not affected by fatigue status. However, females did demonstrate greater estimated knee anterior shear forces post-fatigue with a significant fatigue-gender interaction ($P = 0.01$) noted. The authors concluded that ACL injury prevention programs should incorporate a fatigue component to help minimize the deleterious effects of neuromuscular fatigue on landing biomechanics in all individuals, especially in physically active females.

McLean et al. [28] evaluated ten male and ten female collegiate athletes for the impact of fatigue on gender-based high-risk landing strategies and found that females landed with a greater ankle support strategy (e.g., increased ankle plantar flexion and peak stance ankle supination) and greater knee abduction and knee internal rotation compared to their male counterparts. These authors also reported that fatigue increased initial and peak knee abduction and internal rotation motions, along with peak knee internal rotation, adduction, and abduction moments. Of note was that fatigue caused the females to have a greater amount of knee abduction moments, lending the authors to conclude that dimorphic knee abduction loading in the presence of fatigue may explain the increased injury risk in women. Unfortunately, a lack of prospective epidemiological data supporting this association of the potential compounding effect of fatigue and gender has yet to be undertaken to confirm this theory. Gehring et al. [12] also evaluated the gender effects of isolated joint fatigue on biomechanical landing patterns while performing two-legged landings. Females landed with increased knee flexion velocities and greater knee joint abduction angles compared to males, yet a significant fatigue-gender interaction was not found for these potentially critical biomechanical variables. Perhaps the incorporation of an isolated peripheral fatigue protocol did not present a significant impetus reflective of demonstrating gender-fatigue differences in contrast to the general lower extremity central fatigue-related protocols.

Conclusions

The effects of fatigue on altering biomechanics creating potentially greater ACL injury risk movement patterns have been demonstrated in the literature. Central fatigue studies appear to show greater biomechanical changes compared to peripheral fatigue protocols. A lack of prospective epidemiological studies tracking the physiological state of fatigue and its association with ACL injury risk exists in the current state of the literature. The association of fatigue and injury occurrence is purely speculative at the moment, yet high-quality biomechanical evidence appears to indicate a link between fatigue states and increased biomechanical patterns that may place an individual at greater risk for ACL injury. Additionally, the fatigue effect seems to be greater in females compared to their male counterparts in developing potentially at-risk movement patterns for ACL injury occurrence. Therefore, ACL injury-prevention programs should be designed to prevent the detrimental effects of fatigue. To accomplish this, athletes need to be trained properly to delay the inevitable onset of fatigue and offset the amount of fatigue that does occur. Additionally, it is proposed that instruction on proper movement mechanics while in a fatigued state should be done to allow athletes to develop awareness and motion patterns that may help offset the possible deleterious effects of fatigue on biomechanical motion patterns.

References

1. Agel J, Arendt EA, Bershadsky B (2005) Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. Am J Sports Med 33(4):524–530
2. Arendt E, Dick R (1995) Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. Am J Sports Med 23(6):694–701
3. Benjaminse A, Habu A, Sell TC et al (2008) Fatigue alters lower extremity kinematics during a single-leg stop-jump task. Knee Surg Sports Traumatol Arthrosc 16(4):400–407
4. Boden BP, Dean GS, Feagin JA Jr et al (2000) Mechanisms of anterior cruciate ligament injury. Orthopedics 23(6):573–578
5. Borotikar BS, Newcomer R, Koppes R et al (2008) Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. Clin Biomech (Bristol, Avon) 23(1):81–92
6. Bradley JP, Klimkiewicz JJ, Rytel MJ et al (2002) Anterior cruciate ligament injuries in the National Football League: epidemiology and current treatment trends among team physicians. Arthroscopy 18(5): 502–509
7. Chappell JD, Herman DC, Knight BS et al (2005) Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. Am J Sports Med 33(7): 1022–1029
8. Cortes N, Quammen D, Lucci S et al (2012) A functional agility short-term fatigue protocol changes lower extremity mechanics. J Sports Sci 30(8):797–805
9. Enoka RM, Stuart DG (1992) Neurobiology of muscle fatigue. J Appl Physiol 72(5):1631–1648
10. Gandevia SC, Allen GM, Butler JE et al (1996) Supraspinal factors in human muscle fatigue: evidence for suboptimal output from the motor cortex. J Physiol 490(Pt 2):529–536
11. Gandevia SC (2001) Spinal and supraspinal factors in human muscle fatigue. Physiol Rev 81(4):1725–1789
12. Gehring D, Melnyk M, Gollhofer A (2009) Gender and fatigue have influence on knee joint control strategies during landing. Clin Biomech (Bristol, Avon) 24(1):82–87
13. Greig M, Marchant D, Lovell R et al (2007) A continuous mental task decreases the physiological response to soccer-specific intermittent exercise. Br J Sports Med 41(12):908–913
14. Greig M (2008) The influence of soccer-specific fatigue on peak isokinetic torque production of the knee flexors and extensors. Am J Sports Med 36(7):1403–1409
15. Greig M, Siegler JC (2009) Soccer-specific fatigue and eccentric hamstrings muscle strength. J Athl Train 44(2):180–184
16. Griffin LY, Agel J, Albohm MJ et al (2000) Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. J Am Acad Orthop Surg 8(3):141–150
17. Hakkinen K, Komi PV (1983) Electromyographic and mechanical characteristics of human skeletal muscle during fatigue under voluntary and reflex conditions. Electroencephalogr Clin Neurophysiol 55(4): 436–444
18. Hawkins RD, Fuller CW (1999) A prospective epidemiological study of injuries in four English professional football clubs. Br J Sports Med 33(3):196–203
19. Hawkins RD, Hulse MA, Wilkinson C et al (2001) The association football medical research programme: an audit of injuries in professional football. Br J Sports Med 35(1):43–47
20. Hewett TE, Myer GD, Ford KR et al (2004) Neuromuscular control and valgus loading of the knee predict ACL injury risk in female athletes. Med Sci Sports Exerc 36(5):S287
21. Hewett TE, Myer GD, Ford KR (2006) Anterior cruciate ligament injuries in female athletes: part 1, mechanisms and risk factors. Am J Sports Med 34(2):299–311
22. Hootman JM, Dick R, Agel J (2007) Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. J Athl Train 42(2):311–319
23. Hughes G, Watkins J (2006) A risk-factor model for anterior cruciate ligament injury. Sports Med 36(5): 411–428
24. Kernozek TW, Torry MR, Iwasaki M (2008) Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. Am J Sports Med 36(3):554–565
25. Liederbach M, Dilgen FE, Rose DJ (2008) Incidence of anterior cruciate ligament injuries among elite ballet and modern dancers: a 5-year prospective study. Am J Sports Med 36(9):1779–1788
26. Lucci S, Cortes N, Van Lunen B et al (2011) Knee and hip sagittal and transverse plane changes after two fatigue protocols. J Sci Med Sport 14(5):453–459
27. McLean SG, Huang X, van den Bogert AJ (2005) Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. Clin Biomech (Bristol, Avon) 20(8):863–870
28. McLean SG, Fellin RE, Suedekum N et al (2007) Impact of fatigue on gender-based high-risk landing strategies. Med Sci Sports Exerc 39(3):502–514
29. McLean SG, Samorezov JE (2009) Fatigue-induced ACL injury risk stems from a degradation in central control. Med Sci Sports Exerc 41(8):1661–1672
30. Mihata LC, Beutler AI, Boden BP (2006) Comparing the incidence of anterior cruciate ligament injury in collegiate lacrosse, soccer, and basketball players: implications for anterior cruciate ligament mechanism and prevention. Am J Sports Med 34(6): 899–904
31. Mountcastle SB, Posner M, Kragh JF Jr et al (2007) Gender differences in anterior cruciate ligament injury vary with activity: epidemiology of anterior cruciate ligament injuries in a young, athletic population. Am J Sports Med 35(10):1635–1642

32. Onate J, Cortes N, Welch C et al (2010) Expert versus novice interrater reliability and criterion validity of the landing error scoring system. J Sport Rehabil 19(1):41–56
33. Ostenberg A, Roos H (2000) Injury risk factors in female European football. A prospective study of 123 players during one season. Scand J Med Sci Sports 10(5):279–285
34. Pappas E, Hagins M, Sheikhzadeh A et al (2007) Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. Clin J Sport Med 17(4):263–268
35. Pappas E, Sheikhzadeh A, Hagins M et al (2007) The effect of gender and fatigue on the biomechanics of bilateral landings from a jump: peak values. J Sports Sci Med 6(1):77–84
36. Quammen D, Cortes N, Van Lunen BL et al (2012) Two different fatigue protocols and lower extremity motion patterns during a stop-jump task. J Athl Train 47(1):32–41
37. Rozzi SL, Lephart SM, Gear WS et al (1999) Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. Am J Sports Med 27(3):312–319
38. Sanna G, O'Connor KM (2008) Fatigue-related changes in stance leg mechanics during sidestep cutting maneuvers. Clin Biomech (Bristol, Avon) 23(7):946–954
39. Thomas AC, McLean SG, Palmieri-Smith RM (2010) Quadriceps and hamstrings fatigue alters hip and knee mechanics. J Appl Biomech 26(2):159–170
40. Thomas AC, Palmieri-Smith RM, McLean SG (2011) Isolated hip and ankle fatigue are unlikely risk factors for anterior cruciate ligament injury. Scand J Med Sci Sports 21(3):359–368
41. Uhorchak JM, Scoville CR, Williams GN et al (2003) Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets. Am J Sports Med 31(6):831–842
42. Wojtys EM, Wylie BB, Huston LJ (1996) The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. Am J Sports Med 24(5):615–621
43. Yu B, Garrett WE (2007) Mechanisms of non-contact ACL injuries. Br J Sports Med 41(Suppl 1):i47–i51
44. Zebis MK, Bencke J, Andersen LL et al (2011) Acute fatigue impairs neuromuscular activity of anterior cruciate ligament-agonist muscles in female team handball players. Scand J Med Sci Sports 21(6):833–840

Testing for Neuromuscular Problems and Athletic Performance

13

Sue D. Barber-Westin and Frank R. Noyes

Contents

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 ligament 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 Part III. While some potential factors (such as anatomic or field conditions) may not be alterable, research has shown that high-risk neuromuscular characteristics can be successfully changed which the authors believe may reduce the incidence of noncontact ACL injuries [122]. 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. It is important to also acknowledge that some cost-effective, reliable tests which may correlate with biomechanical indicators of ACL injury risk in

S.D. Barber-Westin, B.S. (✉)
Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA
e-mail: sbwestin@csmref.org

F.R. Noyes, M.D.
Cincinnati Sportsmedicine and Orthopaedic Center, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_13, © Springer-Verlag Berlin Heidelberg 2012

the laboratory have not proven to be predictive of actual future ACL injury. One example is the Landing Error Scoring System, which was recently shown to not be able to predict noncontact ACL injury in a cohort of 5,047 high school and collegiate athletes [141].

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 [17, 90, 119, 136]. 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 and 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 ligament injury prevention programs
- No single test predicts 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

Neuromuscular and Balance

Video Drop-Jump Screening Test

A drop-jump video screening test may be used to measure overall lower-limb alignment in the coronal plane [117]. 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 improvements occurred (Fig. 13.1).

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) take-off, the frame that demonstrates the initial forward and upward movement of the arms and the body as the athlete prepares to go into the maximum vertical jump.

The captured images are imported into a hard drive of a computer and digitized on the screen using commercially available software (Cincinnati Sportsmedicine Research and Education Foundation, Cincinnati, OH). 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. 13.1 The drop-jump land sequences from a 16-year-old female athlete (**a**) before and (**b**) after neuromuscular training. This volleyball player improved in both the absolute cm of knee separation distance (from 15 to 29 cm) and normalized knee separation distance (from 72 to 94 %)

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. 13.2). The authors 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 [117]. Test-retest trials produced high intraclass correlation coefficients (ICC) for the hip separation distance (pre-land, 0.96; land, 0.94; take-off, 0.94). For the within-test trial, the ICCs for the hip, knee, and ankle separation distance were all ≥0.90, demonstrating excellent reliability of the videographic test and software capturing procedures.

If desired, a second camera may be implemented to assess knee and hip flexion angles in the sagittal plane [82]. 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 [29].

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 knee ligament injuries. This test is performed during one maneuver that only depicts hip, knee, and ankle positions in a single plane, whereas noncontact ACL injuries frequently occur

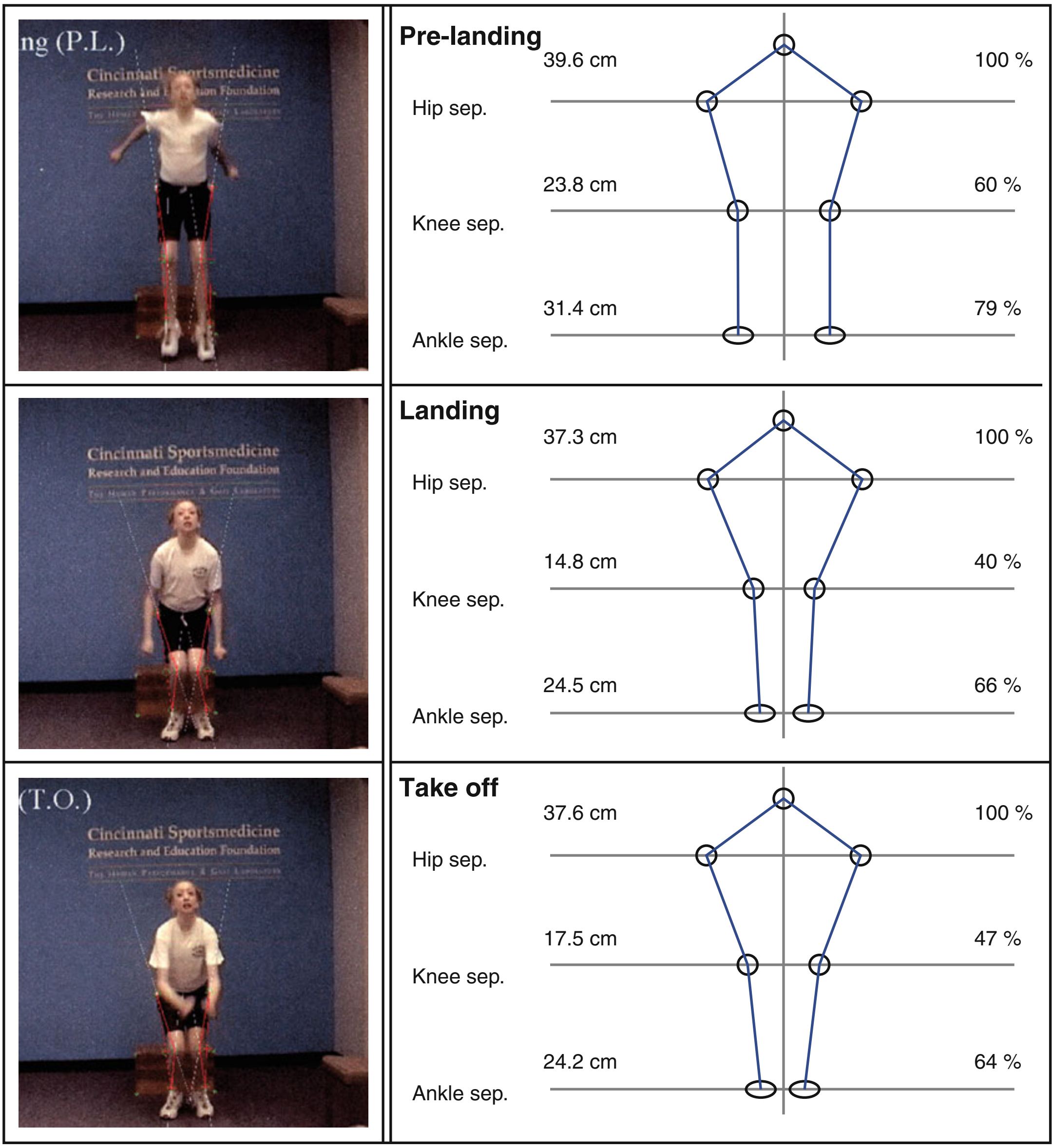


Fig. 13.2 Photographs of the three phases of the drop-jump test. The cm of distance between the hips, knees, and ankles is calculated along with normalized knee and ankle separation distances (according to the hip separation distance). Shown is the test result of a 14-year-old female (Reprinted from Noyes et al. [117]; with permission from SAGE Publications, Inc.)

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. 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.

Single-Leg Functional Hop Tests

Single-leg functional hop tests are worthwhile to conduct to determine if abnormal lower-limb symmetry exists and to subjectively assess the athlete's ability to hop and hold the landing on one leg [116]. These tests are commonly used measures of lower-extremity power and dynamic balance. They are highly reliable and require only a tape measure which is secured to the ground. The tests provide an assessment of single-leg power, balance, control, and a side-to-side comparison of limb symmetry. Research previously conducted by the authors [13] demonstrated that a limb symmetry index of ≥85 % is present in the majority (93 %) of athletes.

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 athlete 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. 13.3a). Some athletes may be able to hold the landing, but their knee may wobble back and forth, and they demonstrate poor upper body control and posture (Fig. 13.3b). In some instances, athletes will not be able to hold the landing at all and may even fall toward the ground (Fig. 13.3c). These athletes 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.

Single-Leg Hop [13, 116]

A tape measure is secured to the ground for a distance of approximately 3 m. The athlete stands on the designated leg to be tested with their toe just behind the starting end of the tape. They are instructed to hop as far as possible forward and land on the same leg, holding that position for at least 2 s (Fig. 13.4a). The athlete is allowed to use their arms for balance as required. After 2–3 trials, the athlete completes 2 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 acceptable reliability, with ICC > 0.85 [63, 128]. Significant correlations have been reported between limb symmetry scores for this test and knee extensor peak torque measured isokinetically [13, 59, 161].

Single-Leg Triple Hop [116]

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. 13.4b). 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 2–3 practice trials, 2 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. The ICC of this test is excellent (0.97 [130]).

Single-Leg Triple Crossover Hop [116]

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. 13.4c). 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 2–3 practice trials, 2 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 acceptable reliability, with ICC > 0.85 [128, 130]. Significant correlations have been reported between limb symmetry scores for this test and knee extensor peak torque measured isokinetically [161].

Fig. 13.3 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**) (Reprinted with permission from Barber-Westin and Noyes [15])

Timed Single-Leg Hop [13, 116]

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 2–3 trials, 2 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 [103, 130]. Significant correlations have been reported between limb symmetry scores for this test and knee extensor peak torque measured isokinetically [161].

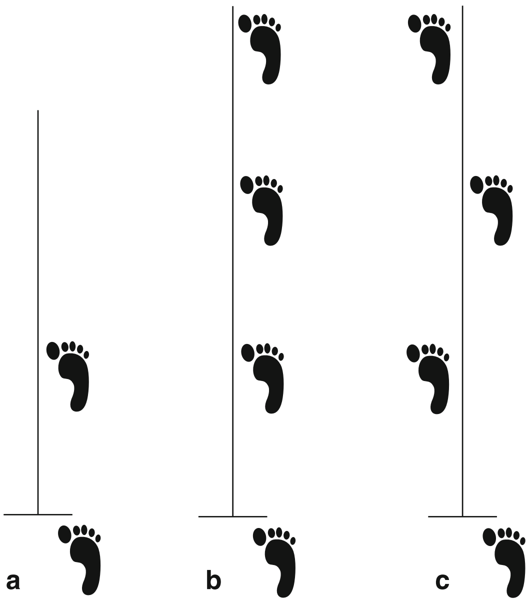


Fig. 13.4 Single-leg hop tests. (**a**) Single hop, (**b**) triple hop, and (**c**) triple crossover hop

Single-Leg Squat Test (See Also Chap. 11)

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 [33]. 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 [167]. Women also assume a greater overall valgus lower-extremity alignment than men [163]. Correlations have been noted between performance on this test in regard to control of frontal plane knee motion and hip muscle strength [31, 33].

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. 13.5). If the foot

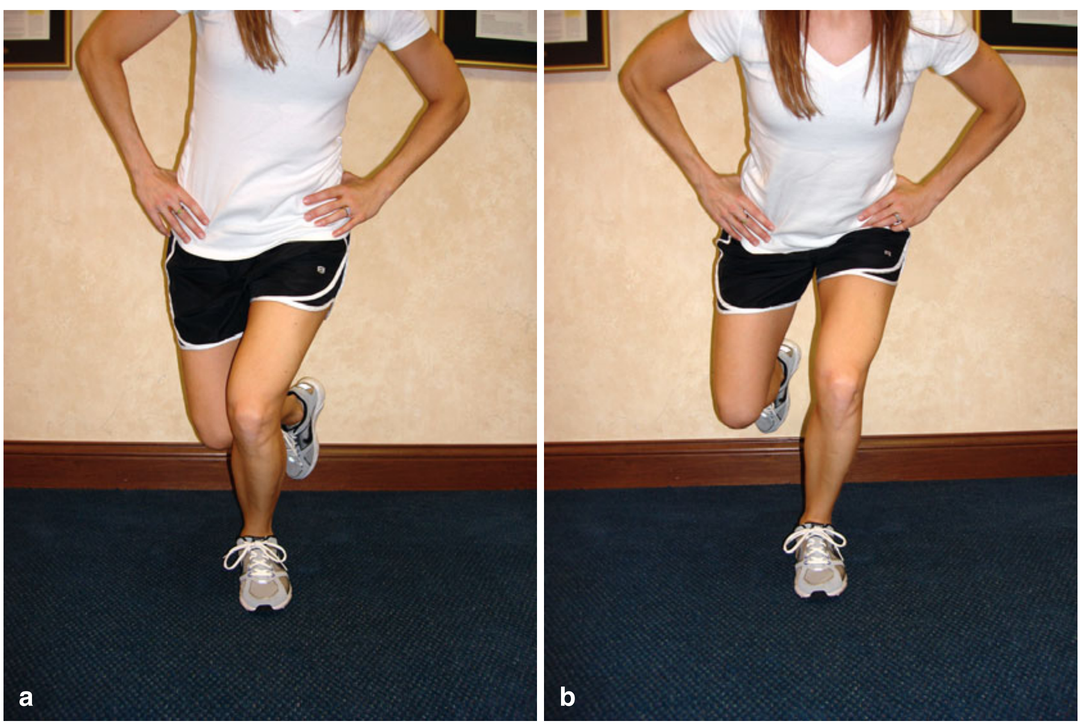


Fig. 13.5 Single-leg squat test. (**a**) Poor hip and knee control and (**b**) good hip, trunk, and knee control

Table 13.1 Clinical rating criteria for the single-leg squat test [33]

Criteria	Criteria to be rated "good"
Overall impression of trial(s)	
Ability to maintain balance	Athlete does not lose balance
Perturbations of the athlete	Movement is performed smoothly
Depth of the squat	The squat is performed to at least 60° knee flexion
Speed of the squat	Squats performed at approximately 1 per 2 s
Trunk posture	
Trunk/thoracic lateral deviation or shift	No trunk/thoracic lateral deviation or shift
Trunk/thoracic rotation	No trunk/thoracic rotation
Trunk/thoracic lateral flexion	No trunk/thoracic lateral flexion
Trunk/thoracic forward flexion	No trunk/thoracic forward flexion
The pelvis "in space"	
Pelvic shunt or lateral deviation	No pelvic shunt or lateral deviation
Pelvic rotation	No pelvic rotation
Pelvic tilt	No pelvic tilt
Hip joint	
Hip adduction	No hip adduction
Hip (femoral) internal rotation	No hip (femoral) internal rotation
Knee joint	
Apparent knee valgus	No apparent knee valgus
Knee position relative to foot position	Center of knee remains over center of foot

s seconds

is touched on the floor or if contact occurs with the other (nonweight-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 13.1) [33]. 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 reliability have been reported [33], with ICC of 0.92 [144].

Star Excursion Balance Test

The Star Excursion Balance Test (SEBT) has been used extensively to measure dynamic postural control in uninjured athletes [19, 44, 62, 112, 124, 131], female athletes who completed neuromuscular retraining [44, 106], patients with chronic ankle instability [61, 69, 118], and individuals with an ACL injury [68]. The task requires the individual to maintain a stable base by balancing on one leg while reaching out with the other leg and touching 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 [118]. This test has adequate reliability for between sessions (ICC, 0.84–0.93 [87, 112, 124]), inter-tester (ICC, 0.81–0.93 [70]), and intra-tester (ICC, 0.81–0.96 [44, 70, 87, 124]) conditions. Studies have reported that patients with chronic ankle instability [61, 69, 118] and ACL deficiency [68] have decreased SEBT reach distances compared to healthy individuals.

The test should be conducted on a firm hard surface, such as concrete or a gymnastics floor, and the athlete should be barefoot. 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. 13.6). 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

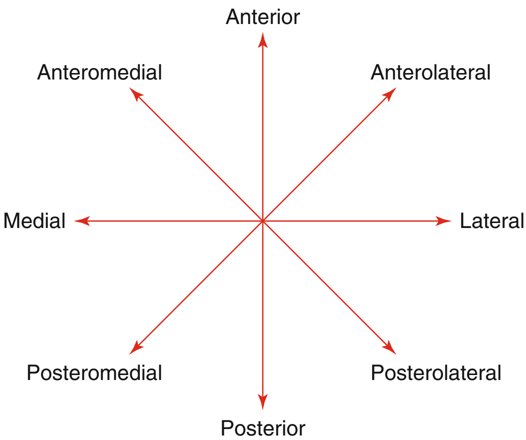


Fig. 13.6 Star Excursion Balance Test. Directions are shown for a right limb stance

Table 13.2 Star Excursion Balance Test normalized results in healthy active collegiate students [112]

Direction	Mean (cm)	95 % confidence interval	SEM	SDD	ICC
Anterior	92.73	92.12–93.34	2.48	6.87	0.84
Anterior-medial	93.43	92.87–94.00	2.21	6.13	0.85
Anterior-lateral	78.60	77.84–79.37	2.78	7.71	0.87
Medial	92.01	91.30–92.71	2.67	7.40	0.86
Lateral	80.43	79.52–81.34	2.77	7.68	0.91
Posterior	87.33	86.36–88.31	2.79	7.73	0.92
Posterior-medial	89.25	88.47–90.02	2.94	8.15	0.86
Posterior-lateral	83.69	82.78–84.61	2.62	7.11	0.92

SDD values are the minimum amount of change needed between two tests for the change to be significant
SEM standard error of measurement, *SDD* smallest detectable difference, *ICC* intraclass correlation coefficient

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 touched 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 touchdown, 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. A total of four practice trials is conducted, followed by three test trials in each direction. A 1-min rest 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, then multiplying by 100 [60]. A change of 6–8 % in normalized scores between independent test sessions is required to detect a clinically significant change according to published smallest detectable difference values (Table 13.2). Investigations to date report no significant difference in reach distance between limbs of uninjured individuals; however, highly trained athletes have greater reach distances than recreational subjects [19, 106, 112, 131, 150]. In addition, collegiate basketball players have smaller reach distances than soccer players [19] and recreational athletes [131] for reasons that remain unclear at present.

Critical Points

- Video drop-jump screening: single coronal plane, <60 % normalized knee separation distance, abnormal lower-limb valgus alignment, and good test-retest and within-test reliability (ICC ≥ 0.90)
- Single-leg hop tests: normal limb symmetry: ≥85 %, correlates with isokinetic knee extensor peak torque, good reliability (ICC > 0.85)
- Single-leg squat test: detects poor hip strength, trunk control, and acceptable interrater and intrarater reliability (ICC 0.92)
- Star Excursion Balance Test: measures dynamic postural control, adequate reliability between sessions (ICC 0.84–0.93), inter-tester (ICC 0.81–0.93), and intra-tester (ICC 0.81–0.96)

Athletic Performance

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. As well, recommendations are made for sports-specific field tests for basketball, soccer, volleyball, and tennis based on the authors' experience and an extensive review of the medical literature. Other resources are available for further test recommendations and procedures [34, 45, 129, 152]. 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.

Before testing, the athlete completes the dynamic warm-up component of Sportsmetrics training (see Chap. 14). Each test is thoroughly explained, and the athlete is allowed several practice trials if required so that they are 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: nonfatiguing (resting heart rate, body composition, flexibility, and jump tests), agility, power and strength, sprints, local muscular endurance, anaerobic capacity, and aerobic capacity tests [66]. Informed consent is obtained from the athletes if they are >18 years of age or from a parent or legal guardian if they are <18 years old. Ideally, the pretrain and posttrain 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 [152]. Longer-lasting tests may require 8 min between repetitions or test trials.

Estimated Maximal Oxygen Uptake: Multistage Fitness Test

Aerobic fitness is a critical component for athletic performance and injury prevention [88]. 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) [95].

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. 13.7). 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

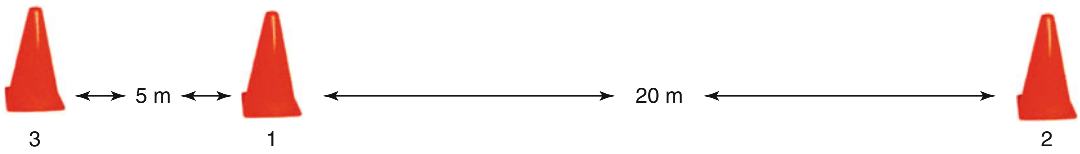


Fig. 13.7 Course used for the 20-m multistage fitness test (cones 1 and 2 only) and the 20-m Yo-Yo intermittent test (cones 1, 2, and 3)

Table 13.3 Predicted maximum oxygen uptake values for multistage fitness test

Level	No. shuttles	Predicted VO_2max	Level	No. shuttles	Predicted VO_2max
4	2	26.8	13	2	57.6
4	4	27.6	13	4	58.2
4	6	28.3	13	6	58.7
4	9	29.5	13	8	59.3
5	2	30.2	13	10	59.8
5	4	31.0	13	13	60.6
5	6	31.8	14	2	61.1
5	9	32.9	14	4	61.7
6	2	33.6	14	6	62.2
6	4	34.3	14	8	62.7
6	6	35.0	14	10	63.2
6	8	35.7	14	13	64.0
6	9	36.4	15	2	64.6
7	2	37.1	15	4	65.1
7	4	37.8	15	6	65.6
7	6	38.5	15	8	66.2
7	8	39.2	15	10	66.7
7	10	39.9	15	13	67.5
8	2	40.5	16	2	68.0
8	4	41.1	16	4	68.5
8	6	41.8	16	6	69.0
8	8	42.4	16	8	69.5
8	10	43.3	16	10	69.9
9	2	43.9	16	12	70.5
9	4	44.5	16	14	70.9
9	6	45.2	17	2	71.4
9	8	45.8	17	4	71.9
9	11	46.8	17	6	72.4
10	2	47.4	17	8	72.9
10	4	48.0	17	10	73.4
10	6	48.7	17	12	73.9
10	8	49.3	17	14	74.4
10	11	50.2	18	2	74.8
11	2	50.8	18	4	75.3
11	4	51.4	18	6	75.8
11	6	51.9	18	8	76.2
11	8	52.5	18	10	76.7
11	10	53.1	18	12	77.2
11	12	53.7	18	15	77.9
12	2	54.3			
12	4	54.8			
12	6	55.4			
12	8	56.0			
12	10	56.5			
12	12	57.1			

From the Department of Physical Education and Sports Science, Loughborough University, 1987

the audio recording are recorded (Table 13.3). The athletes' VO_2max is estimated using the equation described by Ramsbottom et al. [127]:

$$VO_2max = (5.587 \times \text{speed on the last stage}) - 19.458$$

The results may be analyzed according to gender and age-matched percentile groups published by the American College of Sports Medicine [46] (Table 13.4) or compared to those published according to sport and gender (Table 13.5). The MSFT has been used to determine cardiovascular fitness levels in junior rugby league players [47, 49, 55–57], youth soccer players [8, 10, 51, 75, 120, 162], semiprofessional soccer players [20, 114], junior elite basketball players [16], and junior volleyball players [39, 50, 52–54]. Test-retest reliability of the MSFT has been reported by others to be excellent, with ICCs ≥ 0.90 [47, 95, 162].

Intermittent Recovery: Yo-Yo Test

Many sports involve intermittent exercise, such as basketball, soccer, rugby, and tennis. Athletes must be able to perform repeated bouts of intense

Table 13.4 Interpretation of multistage fitness test results according to the American College of Sports Medicine

Gender	Age (years)	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

From the Heywood [74]
Printed in Heyward [73]
Females: estimated VO_2max

Table 13.5 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
Ben Abdelkrim [16]	Basketball, elite, male	18.2 ± 0.5	53.18 ± 2.66
Meckel [107]	Soccer, elite adolescent, male	16–18	54.1 ± 3.1
Nassis [114]	Soccer, semipro, male	22.8 ± 2.5	50.7 ± 3.1
Caldwell [20]	Soccer, semipro, male	24 ± 4.4	58.0 ± 1.9
Hill-Haas [75]	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 [8]	Soccer, elite, male	17.7 ± 0.4	57.8 ± 5.0
Gabbett [51]	Soccer, elite, trained, female	18.3 ± 2.8	48.8 ± 3.6
	Soccer, elite, control, female		52.1 ± 5.1
Siegler [138]	Soccer, elite, male	20 ± 1.5	58.3 ± 5.7
Ostenberg [120]	Soccer, noninjured, baseline, female	20.7 ± 4.6	39.9 ± 5.2
	Soccer, injured, baseline, female		40.6 ± 5.0
Gabbett [50]	Volleyball, IT, male and female	15.6 ± 0.1	45.7 ± 2.0
	Volleyball, SBC, male and female		43.8 ± 2.0
Gabbett [53]	Volleyball, national, male	15.6 ± 0.1	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 [54]	Volleyball, junior, pretrain	15.5 ± 0.2	40.8 ± 1.1
	Volleyball, junior, posttrain		43.2 ± 1.1
	Gender unknown		
Duncan [39]	Volleyball, elite, setters, male	17.5 ± 0.5	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

(continued)

Table 13.5 (continued)

Study	Sport, gender	Age, years	VO_2max
Gabbett [55]	Rugby, league, U-15, male	≤ 14	43.3 ± 1.3
	Rugby, league, U-18, male	15–17	43.4 ± 1.1
Gabbett [56]	Rugby, league, 1st grade, male	22.5 ± 4.9	46.9 ± 5.8
	Rugby, league, 2nd grade, male		45.6 ± 5.7
	Rugby, league, 3rd grade, male		47.6 ± 7.6
Gabbett [48]	Rugby, junior, male	16–17	46.3
	Rugby, senior, male	23–27	44.9
Gabbett [49]	Rugby, elite, forwards, female	18.9 ± 5.7	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

SSG small-sided training program, *GTG* generic training program, *IT* instructional training, *SBC* skill-based conditioning game

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 [9, 10, 22, 91, 92]. The so-called Yo-Yo intermittent recovery test was developed to measure an athlete's ability to repeatedly perform intense exercise [11]. 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. This test has been studied extensively in athletes participating in basketball, soccer, rugby, Australian football, team handball, and running [7, 9–12, 25, 40, 75, 91–94, 111, 115, 126, 135, 143, 160]. It has high reliability, reproducibility, and sensitivity to detect change resulting from training programs; correlates to player position and performance during soccer games; and distinguishes various levels of athletes (i.e., professional, sub-elite, recreational) [11, 23, 28, 75, 92–94, 111, 149, 156].

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. 13.7. The athlete begins with their toes behind the designated starting cone (cone #1 in Fig. 13.7). The second cone is located 20 m away. The athlete is instructed that, on the "go" command (which is an audible beep on the CD), they are to run to the second cone and then return to the starting position when signaled by the recorded beep. They may jog or walk around the third cone and then turn back to the starting cone during a 10-s rest period. The athlete continues to perform this pattern, keeping in time with the series of signals (beeps) on the CD. The frequency of the audible signals (and, hence, running speed) is progressively increased until the athlete reaches volitional exhaustion and can no longer maintain pace with the audio signals. The athletes' level and number of shuttles reached before they were unable to keep up with the audio recording are recorded.

There are two test levels: the Yo-Yo intermittent recovery level 1 (Yo-Yo IR1) test and level 2 (Yo-Yo IR2) test. Level 1 is designated for lesser trained individuals, and level 2 is appropriate for elite and highly trained athletes. 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 13.6 and 13.7). 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 [11]. Instead, it is recommended that the total distance recorded be used to evaluate an athlete's ability to repeatedly perform intermittent exercise (Table 13.8).

Table 13.6 Yo-Yo intermittent recovery test level 1 protocol [24]

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	1,080
8	15.5	8	320	1,400
9	16.0	8	320	1,720
10	16.5	8	320	2,040
11	17.0	8	320	2,360
12	17.5	8	320	2,680
13	18.0	8	320	3,000
14	18.5	8	320	3,320
15	19.0	8	320	3,640

Table 13.7 Yo-Yo intermittent recovery test level 2 protocol [24]

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	1,100
6	14.0	12	240	1,340
7	14.5	13	260	1,600
8	15.0	13	260	1,860
9	15.5	13	260	2,120
10	16.0	14	280	2,400
11	16.5	14	280	2,680
12	17.0	15	300	2,980
13	17.5	15	300	3,280
14	18.0	16	320	3,600

Speed Tests

Sprint Tests: 10, 20, 36.6 m

Sprint tests are used to determine acceleration, speed, and quickness. These tests may be accomplished with 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 one-hundredth of a second. The reliability of sprint tests is excellent, with ICCs > 0.90 using either a handheld stopwatch or timing gates [36, 37, 58, 72]. The results may be compared to published data according to sports and gender (Table 13.9).

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 [36, 37], or tennis court [14]. 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. 13.8). 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 one-hundredths 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.

Agility Tests

T-Test

Since its initial description in the literature in 1990 [134], the *t*-test has become one of the most widely used measures of agility [16, 36, 37, 54, 97, 113]. The athlete sprints from a standing point in a straight line to a cone placed 9 m away (Fig. 13.9). 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

Table 13.8 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
Thomas [149]	Male (23), 19.5–30.7 years	Professional Australian football	NA	708 ± 157
	Male (27), 14.5–18.7 years	State level cricket	1,049 ± 285	NA
	Female (15), 18.4–21.0 years	State level hockey	840 ± 280	NA
	Male (33), 15.2–14.1 years	Recreational athletes (mixed sports)	1,010 ± 419	322 ± 119
Young [166]	Male (34), 22.6 ± 2.9 years	*Professional Australian football*		
		Starters (N = 12)	NA	747 ± 128
		Nonstarters (N = 4)	NA	547 ± 61
		Defenders (N = 7)	NA	743 ± 142
		Forwards (N = 5)	NA	656 ± 128
		Midfielders (N = 6)	NA	747 ± 123
Veale [156]	Male (60), 16.6 ± 0.5 years	Elite youth Australian football (N = 20)	1,910 ± 230	NA
		Sub-elite youth Australian football (N = 20)	1,438 ± 335	NA
		Healthy youth nonathletes (N = 20)	774 ± 358	NA
Serpiello [135]	Male (7) and female (3), 22.3 ± 4.1 years	*Recreational athletes*		
		Pre-train	1,305 ± 709	NA
		Post-repeated sprint train	1,400 ± 715	NA
Bangsbo [11]	Female, 21 years	High-level badminton (N = unknown)	1,200	NA
	Female, 17 years	High-level badminton (N = unknown)	1,080	NA
Bangsbo [11]	Male (20), age unknown	High-level badminton	NA	1,020
Sirotic [140]	Female (16), 20.9 ± 1.8 years	Team sport athletes, regional-level teams	958 ± 368	NA
Bangsbo [11]	Male (13)	Sub-elite ice hockey	NA	510
Bangsbo [11]	Male (32)	Elite and recreational floorball	NA	590
Castagna [25]	Male (22), 16.8 ± 2.0 years	Basketball club	1,678 ± 397	NA
Bangsbo [11]	Male (12)	Junior players of professional basketball club	NA	590
Castagna [22]	Male (42)	*Soccer referees*		
	37.5 ± 4.5 years	Top level (1st, 2nd divisions, N = 14)	1,874 ± 431	NA
	27.8 ± 3.2 years	Medium level (3rd, 4th divisions, N = 14)	1,360 ± 172	NA
	24.8 ± 1.2 years	Low level (3rd, 4th divisions, N = 14)	1,272 ± 215	NA
Krustrup [91]	Male (10), 29–47 years	Soccer referees, top class	1,308 (1,040–1,960)	NA

(continued)

Table 13.8 (continued)

Study	Gender (no.), age	Sport, level	Yo-Yo IR1 test, m	Yo-Yo IR2 test, m
Bangsbo [11]	Male (256), age unknown	Top-elite soccer (*N* = 54)	NA	1,260
		Moderate-elite soccer (*N* = 130)	NA	1,050
		Sub-elite soccer (*N* = 72)	NA	840
Mohr [111]	Male (42), 26.4 ± 0.9 years	Top-class professional soccer (*N* = 18)	2,260 ± 80	NA
		Moderate-class professional soccer (*N* = 24)	2,040 ± 60	NA
Krustrup [92]	Male (37), 22–32 years	*Professional elite soccer*		
		Fullbacks (*N* = 7)	2,241 ± 25	NA
		Central defenders (*N* = 9)	1,919 ± 47	NA
		Attackers (*N* = 8)	1,966 ± 30	NA
		Midfielders (*N* = 13)	2,173 ± 23	NA
Rampinini [126]	Male (25), 25 ± 5 years	Professional soccer (*N* = 13)	2,231 ± 294	958 ± 99
		Amateur soccer (*N* = 12)	1,827 ± 292	613 ± 125
Nicks [115]	Male (20) and female (7), 19.8 ± 0.9 years	*Collegiate soccer*		
		Pre-train	1,250 ± 351	NA
		Post-respiratory muscle training	1,466 ± 486	NA
Castagna [24]	Male (24), 25.6 ± 5.1 years	Amateur adult soccer	2,138 ± 364	NA
Dupont [40]	Male (14), 23.2 + 3.5 years	Amateur adult soccer	2,034 ± 367	NA
Rampinini [125]	Male (20), 24.5 ± 4.1 years	*Amateur adult soccer*		
		Pre-training program	1,986 ± 334	NA
		Post-training program (small-sided games)	2,132 ± 380	NA
Hill-Haas [75]	Male (19), 14.6 ± 0.9 years	*Elite youth soccer*		
		Small-sided game training (*N* = 10)		
		Pre-train	1,488 ± 345	NA
		Post-train	1,742 ± 362	NA
		High-intensity interval training (*N* = 9)		
		Pre-train	1,764 ± 256	NA
		Post-train	2,151 ± 261	NA
Castagna [23]	Male (21), 14.1 ± 0.2 years	Elite youth soccer	842 ± 352	NA
Krustrup [93]	Female (14), 19–31 years	Elite youth soccer	1,379 (600–1,960)	NA

Chaouachi [28]	Male (23), 19 ± 1 years	Elite youth soccer	2,289 ± 409	NA
Malina [102]	Male (69), 13.2–15.1 years	*Novice youth soccer*		
		Tanner stage 1 (*N* = 6)	1,513 ± 301	NA
		Tanner stage 2 (*N* = 10)	2,394 ± 225	NA
		Tanner stage 3 (*N* = 13)	2,492 ± 173	NA
		Tanner stage 4 (*N* = 21)	2,648 ± 136	NA
		Tanner stage 5 (*N* = 19)	2,597 ± 177	NA
Bangsbo [11]	Female (181), age unknown	Top-elite soccer (*N* = 44)	1,600	NA
		Moderate-elite soccer (*N* = 74)	1,360	NA
		Sub-elite soccer (*N* = 63)	1,160	NA
Souhail [143]	Male (18), 14.3 ± 0.5	Team handball	1,831 ± 373	NA

Yo-Yo IR1 Yo-Yo intermittent recovery level 1, *Yo-Yo IR2* Yo-Yo intermittent recovery level 2, *NA* not available

Table 13.9 Sample results of sprint tests according to sport and gender

Study	Sport, gender	Age, years	9.1 m (10 yards), s	10 m (10.9 yards), s	18.2 m (20 yards), s	20 m (21.9 yards), s	27.4 m (30 yards), s	30 m (32.8 yards), s	36.6 m (40 yards), s
Ben Abdelkrim [16]	Basketball, elite, male	18.2 ± 0.5	NA	1.98 ± 0.17	NA	3.23 ± 0.18	NA	4.31 ± 0.18	NA
Delextrat [37]	Basketball, elite, female	NA	NA	NA	NA	3.50 ± 0.23	NA	NA	NA
Delextrat [36]	Basketball, elite, male	NA	NA	NA	NA	3.29 ± 0.12	NA	NA	NA
	Basketball, average, male					3.36 ± 0.36			
Gabbett [58]	Basketball, junior, OS, male & female	16.3 ± 0.7	NA	1.95 ± 0.09	NA	3.34 ± 0.15	NA	NA	NA
	Basketball, junior, CS, male & female			1.97 ± 0.10		3.36 ± 0.18			
Hoffman [78]	Lacrosse, elite, starters, female	19.2 ± 1.0	NA	NA	NA	NA	NA	NA	5.4 ± 0.16
	Lacrosse, elite, nonstarters, female								5.49 ± 0.16
Magal [101]	Soccer, elite, preseason, male	20.0 ± 0.9	NA	20.3 ± 0.15	NA	NA	NA	4.72 ± 0.26	5.86 ± 0.52
	Soccer, elite, postseason, male			1.96 ± 0.11				4.51 ± 0.24	5.79 ± 0.31
Jones [85]	Soccer, field hockey, softball, elite, pre-train	NA	NA	NA	NA	NA	4.83 ± 0.14	NA	NA
	Same, post-train						4.78 ± 0.14		
	All collegiate female								
Mirkov [110]	Soccer, pro, male	20.4 ± 1.8	NA	1.90 ± 0.08	NA	2.52 ± 0.10	NA	NA	NA
Vescovi [158]	Soccer, high school, female	15.1 ± 1.6	1.96 ± 0.10	NA	3.33 ± 0.15	NA	4.63 ± 0.21	NA	5.94 ± 0.28
	Soccer, collegiate, female	19.9 + 0.9	2.00 ± 0.11		3.38 ± 0.17		4.69 ± 0.23		5.99 ± 0.29
	Lacrosse, collegiate, female	19.7 ± 1.1	1.99 ± 0.09		3.37 ± 0.14		4.66 ± 0.20		5.97 ± 0.27
Siegler [138]	Soccer, elite, male	20 ± 1.5	NA	NA	NA	3.01 ± 0.09	NA	NA	NA
Little [98]	Soccer, pro, male	18–36	NA	1.83 ± 0.08	NA	2.40 ± 0.11	NA	NA	NA
Chamari [27]	Soccer, elite, male	17.5 ± 1.1	NA	NA	NA	NA	NA	4.38 ± 0.18	NA
Gabbett [53]	Volleyball, national, male	16.5 ± 0.1	NA	1.80 ± 0.02	NA	NA	NA	NA	NA
	Volleyball, national, female			1.90 ± 0.01					
	Volleyball, state, male			1.76 ± 0.03					
	Volleyball, state, female			1.95 ± 0.02					
	Volleyball, novice, male			1.81 ± 0.02					
	Volleyball, novice, female			2.03 ± 0.03					

Lidor [96]	Volleyball, elite, starters, male	16.4 ± 0.82	NA	2.07 ± 0.13	NA	3.39 ± 0.12	NA	NA	NA
	Volleyball, elite, nonstarters, male			1.99 ± 0.09		3.27 ± 0.16			
Gabbett [54]	Volleyball, junior, pre-train	15.5 ± 0.2	NA	1.95 ± 0.03	NA	NA	NA	NA	NA
	Volleyball, junior, post-train			1.87 ± 0.02					
	Gender unknown								
Gabbett [49]	Rugby, elite, forwards, female	18.9 ± 5.7	NA	2.04 ± 0.10	NA	3.60 ± 0.19	NA	NA	NA
	Rugby, elite, backs, female			1.96 ± 0.10		3.44 ± 0.14			
	Rugby, elite, hit-up forwards, female			2.06 ± 0.11		3.65 ± 0.20			
	Rugby, elite, adjustables, female			1.98 ± 0.05		3.47 ± 0.08			
	Rugby, elite, outside backs, female			1.94 ± 0.13		3.40 ± 0.16			

OS open skills warm-up, *CS* closed skills warm-up, *NA* not available

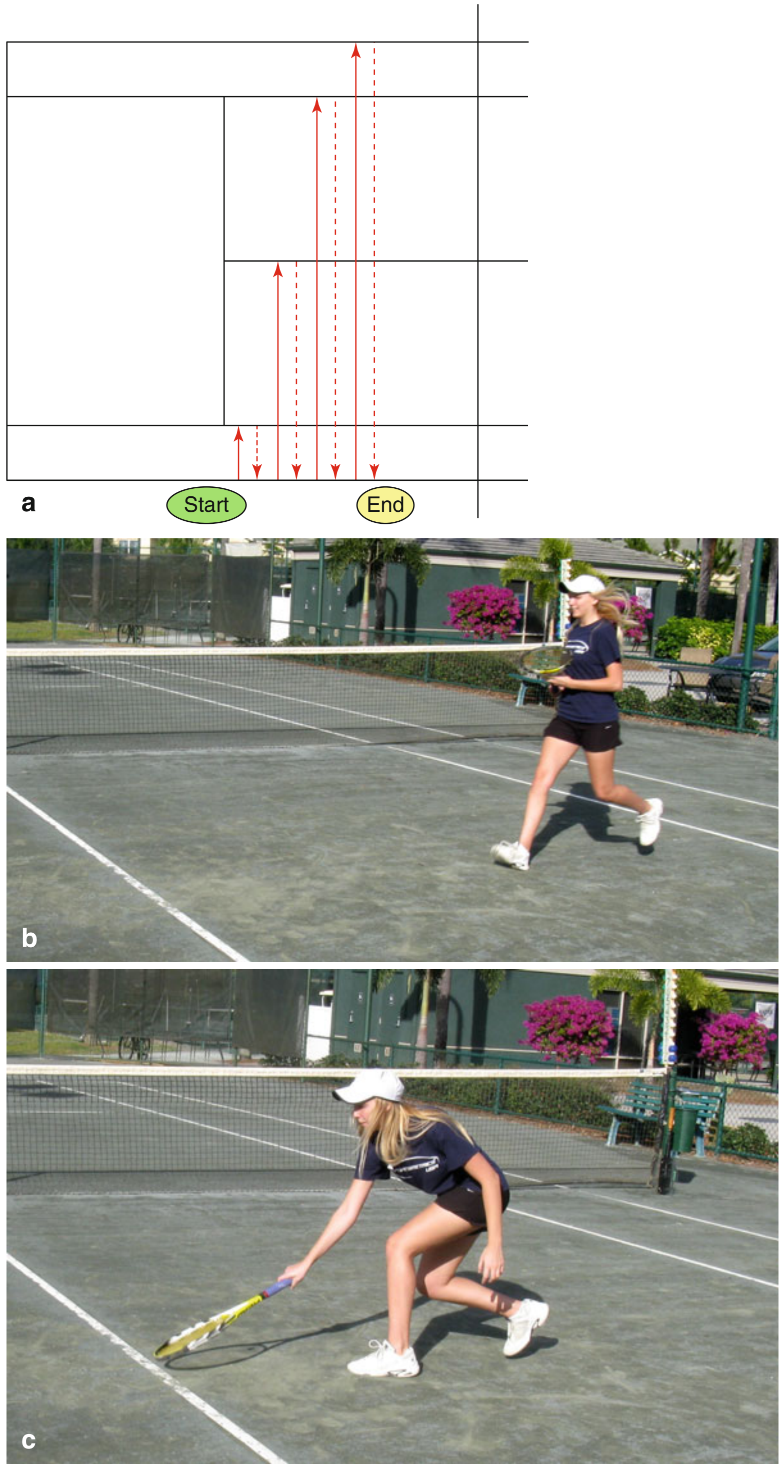


Fig. 13.8 (**a**–**c**) The 1-court suicide is run in a straight line; the figure depicts the eight segments individually for illustrative purposes only. *Solid lines* indicate forward sprinting; *dotted lines* indicate backpedaling

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 one-hundredths of a

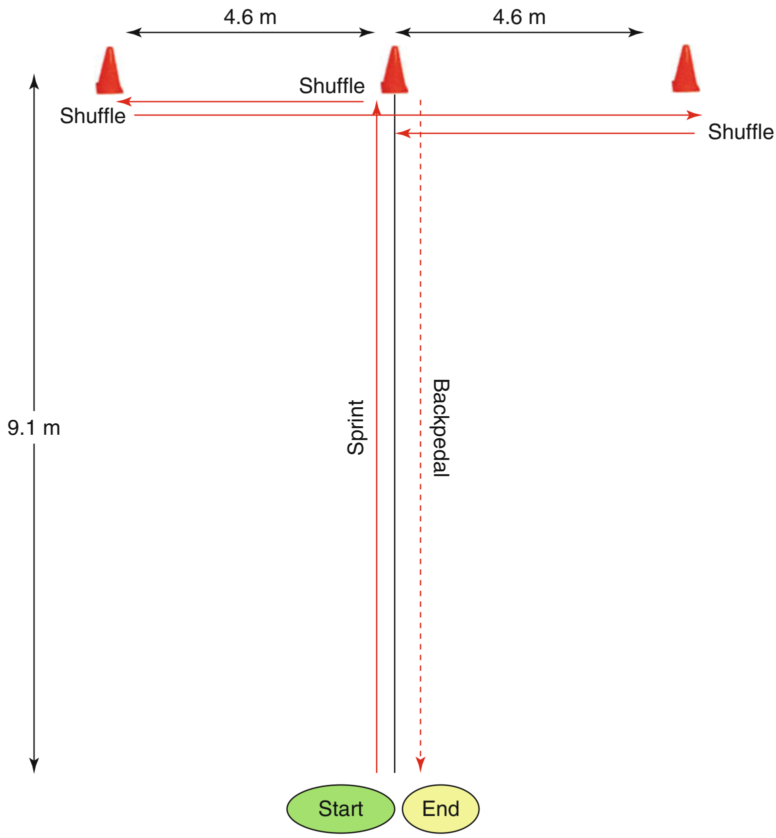


Fig. 13.9 *T*-test. The test requires the athlete to follow the directions shown with the *red arrows* in consecutive order from start to finish

second. This test has excellent reliability, with ICCs ≥ 0.90 [123, 132]. The results may be compared to published data according to sports and gender (Table 13.10).

Pro-Agility Test

Also known as the 5-10-5 test, the pro-agility test is a common field test for soccer players [85, 101]. If done on a marked football field, the athlete begins on the 5-yard line (Fig. 13.10). They sprint 4.5 m to the goal line and touch 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. They are instructed to sprint through the starting point. Two tests are completed, with the best time recorded. The time to complete this test is recorded with a digital stopwatch in one-hundredths of a second. The results may be compared to published data according to sports and gender (Table 13.10).

Baseline Forehand/Backhand Tests [14, 43]

The baseline forehand and backhand tests are useful speed and agility tests for tennis players and are recommended by the Etcheberry Certification for Tennis program [43]. 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. 13.11). 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 1 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

Table 13.10 Sample results of agility tests according to sport and gender

Study	Sport, gender	Age, years	Pro-agility, s	*T*-test, s
Jones [85]	Soccer, field hockey, softball, elite, pre-train, female	NA	5.39 ± 0.24	NA
	Soccer, field hockey, softball, elite, post-train, female	Collegiate	5.37 ± 0.25	
Ben Abdelkrim [16]	Basketball, elite, male	18.2 ± 0.5	NA	11.56 ± 0.46
Delextrat [37]	Basketball, elite, female	NA	NA	10.45 ± 0.51
Delextrat [36]	Basketball, elite, male	NA	NA	9.21 ± 0.24
	Basketball, average level, male			9.78 ± 0.59
Hoffman [78]	Lacrosse, elite, starters, female	19.2 ± 1.0	4.92 ± 0.22	10.5 ± 0.6
	Lacrosse, elite, nonstarters, female		4.94 ± 0.13	10.5 ± 0.2
Vescovi [158]	Soccer, high school, female	15.1 ± 1.6	4.91 ± 0.22	NA
	Soccer, collegiate, female	19.9 ± 0.9	4.88 ± 0.20	
	Lacrosse, collegiate, female	19.7 ± 1.1	4.99 ± 0.24	
Magal [101]	Soccer, elite, pre-season, male	20.0 ± 0.9	4.96 ± 0.19	NA
	Soccer, elite, post-season, male		4.80 ± 0.33	
Gabbett [53]	Volleyball, national, male	16.5 ± 0.1	NA	9.90 ± 0.17
	Volleyball, national, female			10.33 ± 0.13
	Volleyball, state, male			9.76 ± 0.15
	Volleyball, state, female			10.55 ± 0.14
	Volleyball, novice, male			10.47 ± 0.18
	Volleyball, novice, female			11.23 ± 0.16
Gabbett [54]	Volleyball, junior, pre-train	15.5 ± 0.2	NA	11.12 ± 0.16
	Volleyball, junior, post-train			10.54 ± 0.18
	Gender unknown			

NA not available

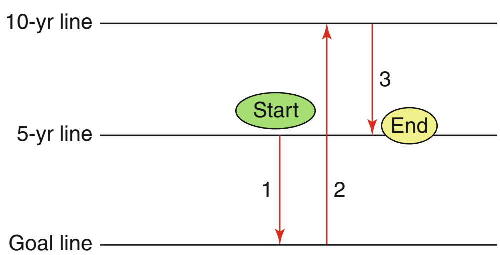


Fig. 13.10 The pro-agility test consists of three forward sprints as shown. Course shown is on an American football field

with the swing cone placed on the singles sideline of the player's backhand.

Service Box Test [14, 43]

The service box test is another appropriate speed and agility test for tennis players that is recommended by the Etcheberry Certification for Tennis program [43]. 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 the singles sideline with their racquet, back and forth, as many times as possible within 30 s which is timed with a digital stopwatch (Fig. 13.12). Each time the player touches a line counts as 1 repetition. The distance between the two lines is 1.1 m. The player performs this test twice, with a 5-min rest between tests. The mean number of repetitions is calculated and converted to the total distance covered. This test has acceptable reliability, with an ICC of 0.85 [14].

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 standing reach is measured with the athlete standing with the heels touching the ground. Then, a countermovement

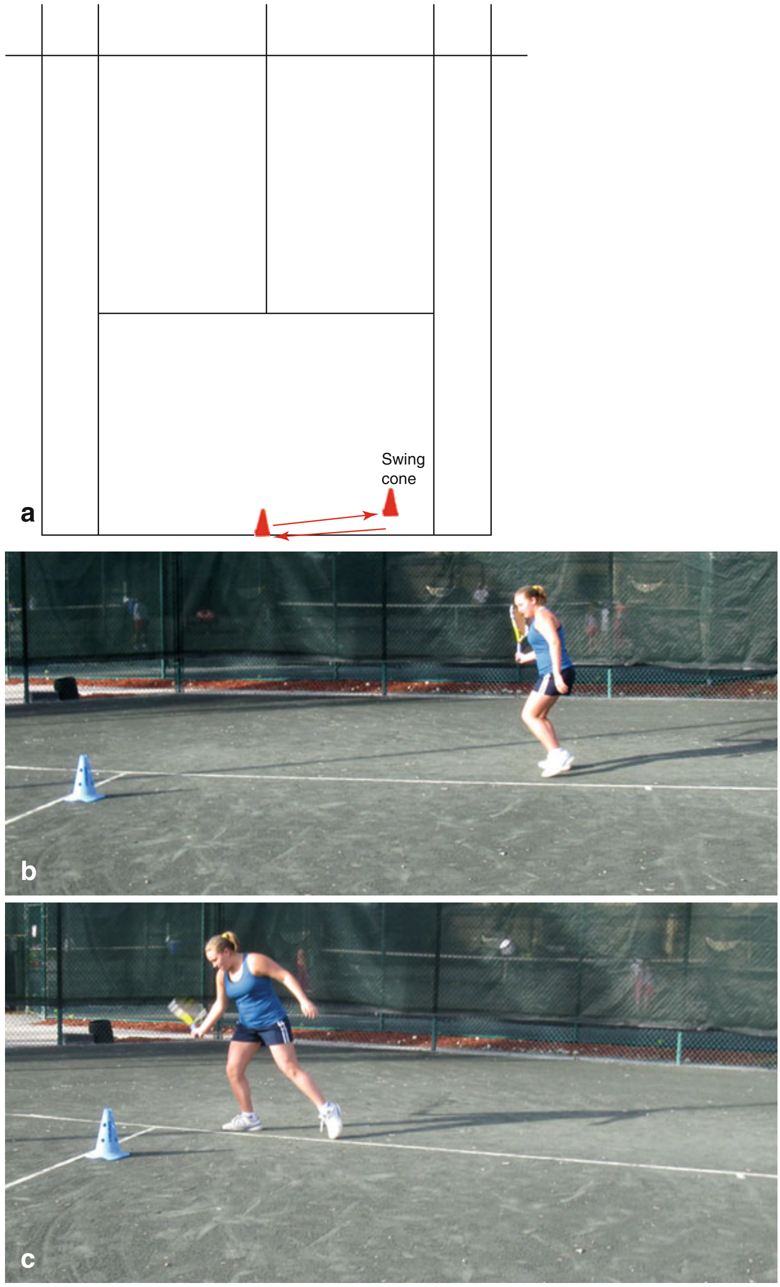


Fig. 13.11 (**a–c**) Baseline speed and agility forehand and backhand test (Reprinted with permission from Barber-Westin et al. [14])

maximum jump with arm swing is performed three times, and the highest jump obtained recorded (Fig. 13.13). Reliability for the assessment of vertical jump height using the Vertec is excellent, with ICCs > 0.90 [30, 165]. The results may be compared to published data according to sports and gender (Table 13.11).

Abdominal Strength

Sit-Up Test [1]

A sit-up test as described by the President's Council on Physical Fitness and Sports may be used to measure abdominal strength. With the athlete lying on their back with the knees bent

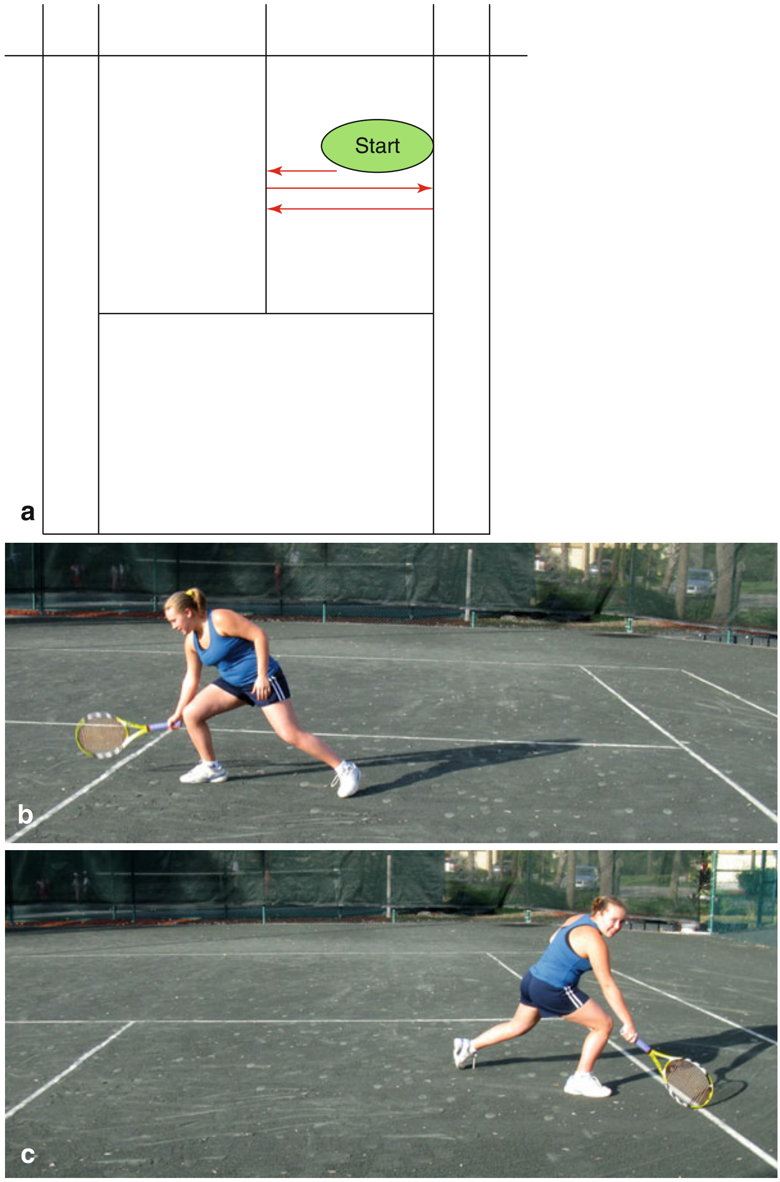


Fig. 13.12 (**a**–**c**) Service box speed and agility test (Reprinted with permission from Barber-Westin et al. [14])

and feet flat on the floor (held in place by a partner) and arms folded across the chest, sit-ups are performed by raising up so that the elbows touch the knees and then lowering back down to the floor. The number of repetitions completed in 60 s is recorded. Other investigations have demonstrated adequate reliability of sit-up tests in normal subjects of 0.84 (reliability coefficient) [2] and chronic pain populations of 0.77 (ICC, test-retest) and 1.0 (ICC, interrater) [65].

Abdominal Endurance Test [14]

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. 13.13 Vertical jump test using the Vertec

Upper Body Strength and Power

Sitting Chest Pass [32]

The sitting chest pass is a convenient way to assess upper body strength and has been used to compare different playing positions in women's basketball players [76]. 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. 13.14). The player is asked to push a basketball in the horizontal direction as far as possible using a 2-handed chest pass. Three trials are completed, with the farthest toss recorded.

Table 13.11 Sample results of countermovement vertical jump height according to sport and gender

Study	Sport, gender	Age, years	Measurement method	Distance, cm
Jones [85]	Soccer, field hockey, softball, elite, pre-train, female	NA	Vertec	48.5 ± 6.3
	Soccer, field hockey, softball, elite, post-train, female	Collegiate		49.8 ± 5.9
Siegler [138]	Soccer, elite, male	20 ± 1.5	Tape measure on wall	60.2 ± 5.7
Chimera [30]	Soccer, field hockey, elite, trained, female	18–22	Vertec	46.2 ± 5.7
	Soccer, field hockey, elite, control, female			45.4 ± 5.8
Hoffman [78]	Lacrosse, elite, starters, female	19.2 ± 1.0	Vertec	38.4 ± 5.6
	Lacrosse, elite, nonstarters, female			36.6 ± 6.1
Enemark-Miller [42]	Lacrosse, elite, female	20.0 ± 1.4	Vertec	44.0 ± 6.2
Gabbett [58]	Basketball, junior, warm-up open skills	16.3 ± 0.7	Yardstick device	50.9 ± 11.0
	Basketball, junior, warm-up closed skills			50.8 ± 10.3
	Male and female			
Myrick [113]	Basketball, junior, pre-train	16–18	Tape measure on wall	48.5
	Basketball, junior, post-train			53.3
	Male and female			
Mihalik [109]	Volleyball, club, complex trained	20.3 ± 2.2	Vertec	48.2 ± 8.6
	Volleyball, club, compound trained	20.9 ± 2.4		47.8 ± 8.0
	Male and female			
Gabbett [53]	Volleyball, national, male	16.5 ± 0.1	Yardstick device	54.6 ± 2.2
	Volleyball, national, female			45.7 ± 1.6
	Volleyball, state, male			63.3 ± 3.2
	Volleyball, state, female			41.5 ± 0.9
	Volleyball, novice, male			48.5 ± 1.0
	Volleyball, novice, female			35.9 ± 1.4
Lidor [96]	Volleyball, elite, starters, male	16.4 ± 0.82	Vertec	57.0 ± 3.7
	Volleyball, elite, nonstarters, male			54.3 ± 2.5

(continued)

Table 13.11 (continued)

Study	Sport, gender	Age, years	Measurement method	Distance, cm
Gabbett [54]	Volleyball, junior, pre-train	15.5 ± 0.2	Yardstick device	45.7 ± 2.3
	Volleyball, junior, post-train			45.7 ± 2.4
	Gender unknown			
Gabbett [49]	Rugby, elite, forwards, female	18.9 ± 5.7	Yardstick device	35.1 ± 8.0
	Rugby, elite, backs, female			35.7 ± 5.9
	Rugby, elite, hit-up forwards, female			34.3 ± 8.6
	Rugby, elite, adjustables, female			35.6 ± 5.5
	Rugby, elite, outside backs, female			37.0 ± 7.0

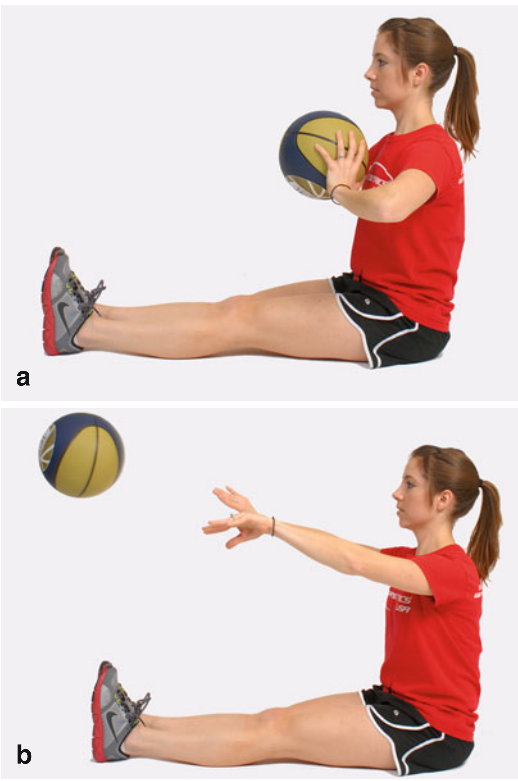


Fig. 13.14 (**a**, **b**) Sitting chest pass

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. 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 (Fig. 13.15a–d). Three trials are completed, with the farthest toss recorded. Significant correlations were reported between this test and isometric maximum trunk rotation torque and 1-repetition maximum bench press for male athletes [83]. 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 [41].

Sports-Specific Field Test Recommendations

Table 13.12 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 [16, 26, 27, 30, 32, 36–38, 41, 45, 54, 58, 63, 72, 76, 77, 83, 85, 96–98, 101, 103, 107, 110, 113, 123, 127–130, 132, 137, 138, 146, 157, 158, 165, 168]. 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 1-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 [89, 129]. For these tests, the athlete should

Fig. 13.15 Medicine ball toss for tennis players. (**a**, **b**) Backhand. (**c**, **d**) Overhead

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. Then, the weight is increased and

Table 13.12 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 Dribbling 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, and overhead Yo-Yo test	Star Excursion Balance Test 1-rep max bench press, leg press Multistage fitness test

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 [129].

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 [79]. The gym floor is marked with five spots at a distance 4.5 m from the center of the backboard (Fig. 13.16). First, a 6-min warm-up is completed which consists of layups and spot-shooting with a partner. Then, over a 1-min period, the athlete shoots from each of the five spots at least once and as many times as possible. The athlete retrieves their own ball and dribbles to a subsequent spot. Four layup shots are allowed, but no two layups in

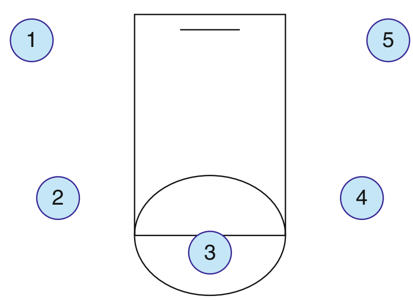


Fig. 13.16 Speed shot shooting test. Each spot numbered *1–5* is 4.5 m from the center of the backboard

succession. Each basket made equals 2 points and the total points are recorded. The ICC of this test is 0.95 for high school and 0.91 for collegiate female players [79]. The results may be placed into percentile groups according to gender and age (Table 13.13).

A second basketball test involves a controlled dribble [79]. An obstacle course is marked using six cones in the free throw lane of the court (Fig. 13.17). The athlete starts on the nondominant hand side of the first cone. On command, the athlete dribbles with the nondominant hand to the nondominant 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 (Table 13.14) [79].

Table 13.13 Speed shot shooting percentile norms for female athletes [79]

Percentile	Age, years			
	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

There have been many cognitive-, skill-, and technique-based tests published for soccer [3]. Ali [3] conducted an extensive review of these tests, many of which failed to provide reliability or validity data. In elite players, tests such as the Loughborough Soccer Passing Test and Loughborough Soccer Shooting Test may be used to determine their ability to perform multiple skills such as dribbling, passing, shooting, and sprinting [4, 5]. 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. [104, 105] 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. 13.18). 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 and associates [64] described a similar dribbling test to that of McGregor; however, only five

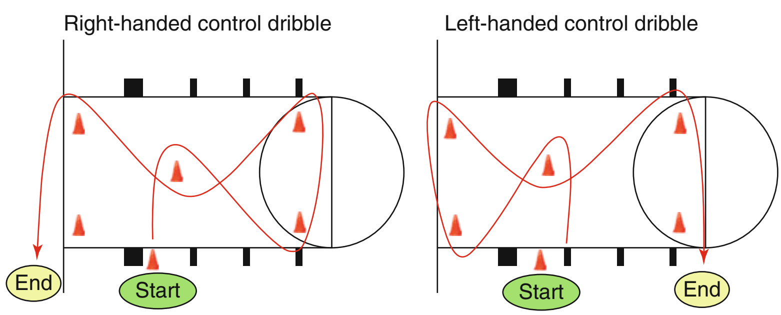


Fig. 13.17 Controlled dribble test course

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. [155] 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 [155].

Table 13.14 Controlled dribbling percentile norms for female athletes [79]

Percentile	Age, years			
	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	9.0
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	12.0	12.0	12.2	10.4
20	12.3	12.4	12.7	10.7
15	12.6	13.0	13.0	11.2
10	13.6	13.7	13.9	11.8
5	18.1	15.8	15.0	13.8

Critical Points

- Field tests should have acceptable reliability in measuring specific functional tasks.
- Explain test, 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, 2 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, 1-repetition maximum bench press.

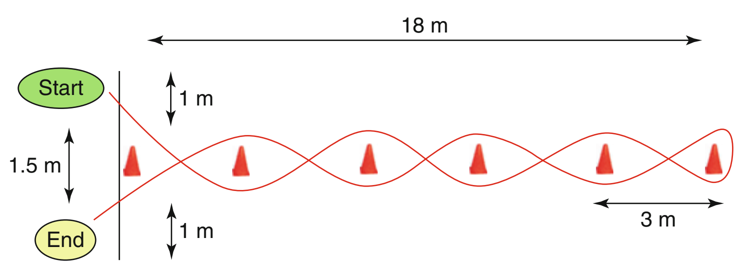


Fig. 13.18 Course for the Loughborough Soccer Dribbling Test

Other Testing Considerations

Body Mass Index

Uhorchak et al. [153] reported that a higher than average body mass index (BMI) was a risk factor for noncontact ACL injuries in female cadets (Table 13.15). 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. Body mass index is calculated as weight (in kilograms)/height (in meters) squared.

Femoral Notch Width

Some investigators have reported that a narrow femoral notch width is a risk factor for noncontact ACL injuries [35, 80, 84, 100, 139, 153], although others have refuted this finding [71, 99, 108, 133, 148, 159]. In a multivariate model, Uhorchak et al. [153] found that the combination of a narrow femoral notch width, higher than average BMI, and generalized joint laxity explained 62.5 % of the variability in noncontact ACL tears ($R^2 = 0.625$). A narrow notch width was defined as 1 standard deviation below the mean value of 15.6 ± 2.9 mm obtained from 113 women. In that investigation, notch width was measured on standard tunnel radiographs in which a line was drawn parallel to the tibial plateau through the femoral condyles and intercondylar notch at the level of the lateral sulcus. The authors stated that their results did "not add any insight into whether narrow femoral notch width is a risk factor for noncontact ACL injuries or merely a noticeable radiographic finding that is associated with ACL size." They did suggest, however, that women and men with narrow femoral notches may be at higher risk for injury than those with larger notches, regardless of whether the notch size itself contributes to ACL injuries. Criticisms of using radiographs to measure notch width are that this technique provides only a single plane measurement and not a three-dimensional area of the actual size of the ACL and is overall inaccurate in measuring actual notch size [6, 154]. Magnetic resonance imaging (MRI) provides a more accurate measurement of intercondylar notch width [80].

Tibial Slope

Recent studies have reported potential associations between increases in tibial slope measured either on radiographs or MRI and noncontact ACL injuries [18, 67, 139, 142, 145, 151, 159]. 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 [159]. Another reported an increase in posterior tibial slope in 45 females who had sustained noncontact ACL injuries compared to 53 controls [151]. A significantly steeper lateral posterior tibial slope was measured on MRI in 27 ACL-injured male subjects compared to 27 controls [139]. Hashemi et al. [67] concluded 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. MRI techniques continue to emerge to more precisely measure knee geometry [81, 86, 142].

Generalized Joint Laxity

Generalized joint laxity may be a risk factor for noncontact ACL injuries as reported by Uhorchak et al. [153]. Pacey et al. [121], 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 odds ratios 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 ($P < 0.001$).

Table 13.15 Significant comparisons: noncontact ACL injury versus no ACL injury in female cadets

Risk factor	ACL	No.	Mean ± SD	Range	*P* value
Body weight, kg	Injured	8	66.5 ± 5.7	58.5–75.3	0.019
	Uninjured	110	60.3 ± 7.2	44.5–80.3	
Body mass index	Injured	8	24.1 ± 1.2	22.2–25.4	0.008
	Uninjured	110	22.1 ± 2.1	18.5–28.6	
Notch width, mm	Injured	8	11.6 ± 2.6	9.0–16.0	<0.001
	Uninjured	105	15.5 ± 2.8	9.0–24.0	
Generalized laxity (no. regions)	Injured	8	4.6 ± 2.5	0–8	0.01
	Uninjured	112	3.2 ± 2.4	0–8	

Table 13.16 ACL noncontact injury risk screening for female athletes

Factor	Method	Possible risk factor results
Body mass index	Weight (kg)/height (m)^2	>24
Femoral notch index	Radiograph, see text	<12.7 mm
Generalized joint laxity [21]	1 point each side Passive hyperextension finger, lies parallel to forearm Passive apposition of thumb to flexor aspect of forearm Hyperextension elbow >10° Hyperextension knee >10° Dorsiflexion ankle >30°	Total score ≥5 points
Drop-jump video test	Normalized knee separation distance	>60 %
Single-leg triple hop test	Limb symmetry	<85 %

The assessment used by Uhorchak and associates of the 8-point scale proposed by Wynne-Davies [164] included small-finger metacarpophalangeal hyperextension (≥90° of extension), elbow hyperextension, knee hyperextension, and the ability to touch the thumb to the volar aspect of the forearm. Generalized joint laxity was considered present when five or more of these signs were observed bilaterally and in at least three joints. Carter and Wilkinson [21] also published a rating scale for assessing generalized joint laxity in which five factors are rated on each side to produce a total score of 10 possible points (Table 13.16). A score of 5 points or greater indicates generalized joint laxity.

Neurocognitive Function Testing

To date, only one study has investigated a potential association between neurocognitive performance and noncontact ACL injuries. Swanik et al. [147] 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 to 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. The authors cautioned that further work was required to determine if deficits in higher brain center neurocognitive function could be clearly linked to dynamic restraint mechanisms. No gender comparison was performed in this study.

Critical Points

- Body mass index >24 in females aged 17–23 years risk factor ACL injury in 1 study.
- Narrow femoral notch width questionable risk factor.
- Generalized joint laxity: meta-analysis showed significant increased knee joint injuries in hypermobile patients.
- Neurocognitive function testing (mPACT): low average to average scores for reaction times, processing speeds, visual memory scores, and verbal memory scores in patients who sustained ACL injuries.

References

1. 1985 National School Population Fitness Survey from President's Council on Physical Fitness and Sports (1986). Washington, D.C.
2. Alaranta H, Hurri H, Heliovaara M et al (1994) Non-dynamometric trunk performance tests: reliability and normative data. Scand J Rehabil Med 26(4):211–215
3. Ali A (2011) Measuring soccer skill performance: a review. Scand J Med Sci Sports 21(2):170–183
4. Ali A, Foskett A, Gant N (2008) Validation of a soccer skill test for use with females. Int J Sports Med 29(11):917–921
5. Ali A, Williams C, Hulse M et al (2007) Reliability and validity of two tests of soccer skill. J Sports Sci 25(13):1461–1470
6. Anderson AF, Anderson CN, Gorman TM et al (2007) Radiographic measurements of the intercondylar notch: are they accurate? Arthroscopy 23(3):261–268, 268.e261–262
7. Atkins SJ (2006) Performance of the Yo-Yo Intermittent Recovery Test by elite professional and semiprofessional rugby league players. J Strength Cond Res 20(1):222–225
8. Aziz AR, Chia MY, Teh KC (2005) Measured maximal oxygen uptake in a multi-stage shuttle test and treadmill-run test in trained athletes. J Sports Med Phys Fitness 45(3):306–314
9. Aziz AR, Mukherjee S, Chia MY et al (2007) Relationship between measured maximal oxygen uptake and aerobic endurance performance with running repeated sprint ability in young elite soccer players. J Sports Med Phys Fitness 47(4):401–407
10. Aziz AR, Tan FHY, Teh KC (2005) A pilot study comparing two field tests with the treadmill run test in soccer players. J Sports Sci Med 4:105–112
11. Bangsbo J, Iaia FM, Krustrup P (2008) The Yo-Yo intermittent recovery test: a useful tool for evaluation of physical performance in intermittent sports. Sports Med 38(1):37–51
12. Bangsbo J, Mohr M, Krustrup P (2006) Physical and metabolic demands of training and match-play in the elite football player. J Sports Sci 24(7):665–674
13. Barber SD, Noyes FR, Mangine RE et al (1990) Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. Clin Orthop 255:204–214
14. Barber-Westin SD, Hermeto AA, Noyes FR (2010) A 6-week neuromuscular training program for competitive junior tennis players. J Strength Cond Res 24(9):2372–2382
15. Barber-Westin SD, Noyes FR (2009) Decreasing the risk of anterior cruciate ligament injuries in female athletes. In: Noyes FR (ed) Noyes' Knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 428–463
16. Ben Abdelkrim N, Castagna C, Jabri I et al (2010) Activity profile and physiological requirements of junior elite basketball players in relation to aerobic-anaerobic fitness. J Strength Cond Res 24(9):2330–2342
17. Boden BP, Torg JS, Knowles SB et al (2009) Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. Am J Sports Med 37(2):252–259
18. Brandon ML, Haynes PT, Bonamo JR et al (2006) The association between posterior-inferior tibial slope and anterior cruciate ligament insufficiency. Arthroscopy 22(8):894–899
19. Bressel E, Yonker JC, Kras J et al (2007) Comparison of static and dynamic balance in female collegiate soccer, basketball, and gymnastics athletes. J Athl Train 42(1):42–46
20. Caldwell BP, Peters DM (2009) Seasonal variation in physiological fitness of a semiprofessional soccer team. J Strength Cond Res 23(5):1370–1377
21. Carter C, Wilkinson J (1964) Persistent joint laxity and congenital dislocation of the hip. J Bone Joint Surg Br 46:40–45
22. Castagna C, Abt G, D'Ottavio S (2005) Competitive-level differences in Yo-Yo intermittent recovery and

twelve minute run test performance in soccer referees. J Strength Cond Res 19(4):805–809
23. Castagna C, Impellizzeri F, Cecchini E et al (2009) Effects of intermittent-endurance fitness on match performance in young male soccer players. J Strength Cond Res 23(7):1954–1959
24. Castagna C, Impellizzeri FM, Chamari K et al (2006) Aerobic fitness and yo-yo continuous and intermittent tests performances in soccer players: a correlation study. J Strength Cond Res 20(2):320–325
25. Castagna C, Impellizzeri FM, Rampinini E et al (2008) The Yo-Yo intermittent recovery test in basketball players. J Sci Med Sport 11(2):202–208
26. Chamari K, Chaouachi A, Hambli M et al (2008) The five-jump test for distance as a field test to assess lower limb explosive power in soccer players. J Strength Cond Res 22(3):944–950
27. Chamari K, Hachana Y, Ahmed YB et al (2004) Field and laboratory testing in young elite soccer players. Br J Sports Med 38(2):191–196
28. Chaouachi A, Manzi V, del Wong P et al (2010) Intermittent endurance and repeated sprint ability in soccer players. J Strength Cond Res 24(10):2663–2669
29. Chaudhart AM, Hearn BK, Leveille LA et al (2003) The effects of dynamic limb alignment on knee moments during single limb landing: implications for the analysis of the non-contact injury to the anterior cruciate ligament. In: 2003 summer bioengineering conference, Key Biscayne, 25–29 June 2003
30. Chimera NJ, Swanik KA, Swanik CB et al (2004) Effects of plyometric training on muscle-activation strategies and performance in female athletes. J Athl Train 39(1):24–31
31. Claiborne TL, Armstrong CW, Gandhi V et al (2006) Relationship between hip and knee strength and knee valgus during a single leg squat. J Appl Biomech 22(1):41–50
32. Cronin JB, Owen GJ (2004) Upper-body strength and power assessment in women using a chest pass. J Strength Cond Res 18(3):401–404
33. Crossley KM, Zhang WJ, Schache AG et al (2011) Performance on the single-Leg squat task indicates hip abductor muscle function. Am J Sports Med 39(4):866–873
34. Currell K, Jeukendrup AE (2008) Validity, reliability and sensitivity of measures of sporting performance. Sports Med 38(4):297–316
35. Davis TJ, Shelbourne KD, Klootwyk TE (1999) Correlation of the intercondylar notch width of the femur to the width of the anterior and posterior cruciate ligaments. Knee Surg Sports Traumatol Arthrosc 7(4):209–214
36. Delextrat A, Cohen D (2008) Physiological testing of basketball players: toward a standard evaluation of anaerobic fitness. J Strength Cond Res 22(4):1066–1072
37. Delextrat A, Cohen D (2009) Strength, power, speed, and agility of women basketball players according to playing position. J Strength Cond Res 23(7):1974–1981
38. Drinkwater EJ, Pyne DB, McKenna MJ (2008) Design and interpretation of anthropometric and fitness testing of basketball players. Sports Med 38(7):565–578
39. Duncan MJ, Woodfield L, al-Nakeeb Y (2006) Anthropometric and physiological characteristics of junior elite volleyball players. Br J Sports Med 40(7):649–651; discussion 651
40. Dupont G, Defontaine M, Bosquet L et al (2010) Yo-Yo intermittent recovery test versus the Universite de Montreal Track Test: relation with a high-intensity intermittent exercise. J Sci Med Sport 13(1):146–150
41. Ellenbecker TS, Roetert EP (2004) An isokinetic profile of trunk rotation strength in elite tennis players. Med Sci Sports Exerc 36(11):1959–1963
42. Enemark-Miller EA, Seegmiller JG, Rana SR (2009) Physiological profile of women's Lacrosse players. J Strength Cond Res 23(1):39–43
43. Etcheberry P (2009) Etcheberry Certificaton for Tennis. http://etcheberryexperience.com/en/info/tennis_certification. Accessed 17 Dec 2009
44. Filipa A, Byrnes R, Paterno MV et al (2010) Neuromuscular training improves performance on the star excursion balance test in young female athletes. J Orthop Sports Phys Ther 40(9):551–558
45. Foran B (2001) High-performance sports conditioning. Human Kinetics, Champaign
46. Franklin BA, Whaley MH, Howley ET (2009) ACSM's guidelines for exercise testing and prescription, 6th edn. Lippincott Williams & Wilkins, Baltimore
47. Gabbett TJ (2005) A comparison of physiological and anthropometric characteristics among playing positions in junior rugby league players. Br J Sports Med 39(9):675–680
48. Gabbett TJ (2006) Performance changes following a field conditioning program in junior and senior rugby league players. J Strength Cond Res 20(1):215–221
49. Gabbett TJ (2007) Physiological and anthropometric characteristics of elite women rugby league players. J Strength Cond Res 21(3):875–881
50. Gabbett TJ (2008) Do skill-based conditioning games offer a specific training stimulus for junior elite volleyball players? J Strength Cond Res 22(2):509–517
51. Gabbett TJ, Carius J, Mulvey M (2008) Does improved decision-making ability reduce the physiological demands of game-based activities in field sport athletes? J Strength Cond Res 22(6):2027–2035
52. Gabbett TJ, Georgieff B (2006) The development of a standardized skill assessment for junior volleyball players. Int J Sports Physiol Perform 1(2):95–107
53. Gabbett T, Georgieff B (2007) Physiological and anthropometric characteristics of Australian junior national, state, and novice volleyball players. J Strength Cond Res 21(3):902–908
54. Gabbett T, Georgieff B, Anderson S et al (2006) Changes in skill and physical fitness following training in talent-identified volleyball players. J Strength Cond Res 20(1):29–35
55. Gabbett TJ, Johns J, Riemann M (2008) Performance changes following training in junior rugby league players. J Strength Cond Res 22(3):910–917
56. Gabbett T, Kelly J, Pezet T (2007) Relationship between physical fitness and playing ability in rugby league players. J Strength Cond Res 21(4):1126–1133

57. Gabbett T, Kelly J, Pezet T (2008) A comparison of fitness and skill among playing positions in sub-elite rugby league players. J Sci Med Sport 11(6):585–592
58. Gabbett TJ, Sheppard JM, Pritchard-Peschek KR et al (2008) Influence of closed skill and open skill warm-ups on the performance of speed, change of direction speed, vertical jump, and reactive agility in team sport athletes. J Strength Cond Res 22(5):1413–1415
59. Greenberger HB, Paterno MV (1995) Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. J Orthop Sports Phys Ther 22(5):202–206
60. Gribble PA, Hertel J (2003) Considerations for normalising measures of the star excursion balance test. Meas Phys Educ Exer Sci 7(2):89–100
61. Gribble PA, Hertel J, Denegar CR et al (2004) The effects of fatigue and chronic ankle instability on dynamic postural control. J Athl Train 39(4):321–329
62. Gribble PA, Robinson RH, Hertel J et al (2009) The effects of gender and fatigue on dynamic postural control. J Sport Rehabil 18(2):240–257
63. Gustavsson A, Neeter C, Thomee P et al (2006) A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 14(8):778–788
64. Haaland E, Hoff J (2003) Non-dominant leg training improves the bilateral motor performance of soccer players. Scand J Med Sci Sports 13(3):179–184
65. Harding VR, Williams AC, Richardson PH et al (1994) The development of a battery of measures for assessing physical functioning of chronic pain patients. Pain 58(3):367–375
66. Harman EA (2008) Principles of test selection and administration. In: Beachle TR, Earle RW (eds) Essentials of strength training and conditioning, 3rd edn. Human Kinetics, Champaign, pp 238–246
67. Hashemi J, Chandrashekar N, Mansouri H et al (2010) Shallow medial tibial plateau and steep medial and lateral tibial slopes: new risk factors for anterior cruciate ligament injuries. Am J Sports Med 38(1):54–62
68. Herrington L, Hatcher J, Hatcher A et al (2009) A comparison of Star Excursion Balance Test reach distances between ACL deficient patients and asymptomatic controls. Knee 16(2):149–152
69. Hertel J, Braham RA, Hale SA et al (2006) Simplifying the star excursion balance test: analyses of subjects with and without chronic ankle instability. J Orthop Sports Phys Ther 36(3):131–137
70. Hertel J, Miller SJ, Denegar CR (2000) Intratester and intertester reliability during the Star Excurision Balance Tests. J Sport Rehabil 9:104–116
71. Herzog RJ, Silliman JF, Hutton K et al (1994) Measurements of the intercondylar notch by plain film radiography and magnetic resonance imaging. Am J Sports Med 22(2):204–210
72. Hetzler RK, Stickley CD, Lundquist KM et al (2008) Reliability and accuracy of handheld stopwatches compared with electronic timing in measuring sprint performance. J Strength Cond Res 22(6):1969–1976
73. Heyward VH (1998) Advance fitness assessment & exercise prescription, 3rd edn. Human Kinetics Pub, Champaign, p 48
74. Heywood V (1998) Physical fitness specialist certification manual. The Cooper Institute for Aerobics Research, Dallas, X, revised 1997
75. Hill-Haas SV, Coutts AJ, Rowsell GJ et al (2009) Generic versus small-sided game training in soccer. Int J Sports Med 30(9):636–642
76. Hoare DG (2000) Predicting success in junior elite basketball players – the contribution of anthropometic and physiological attributes. J Sci Med Sport 3(4): 391–405
77. Hoff J (2005) Training and testing physical capacities for elite soccer players. J Sports Sci 23(6):573–582
78. Hoffman JR, Ratamess NA, Neese KL et al (2009) Physical performance characteristics in National Collegiate Athletic Association Division III champion female lacrosse athletes. J Strength Cond Res 23(5):1524–1529
79. Hopkins DR, Shick J, Plack JJ (1984) Basketball for boys and girls: skills test manual. Alliance for Health, Physical Education, Recreation and Dance, Reston, p 18
80. Hoteya K, Kato Y, Motojima S et al (2011) Association between intercondylar notch narrowing and bilateral anterior cruciate ligament injuries in athletes. Arch Orthop Trauma Surg 131(3):371–376
81. Hudek R, Fuchs B, Regenfelder F et al (2011) Is non-contact ACL injury associated with the posterior tibial and meniscal slope? Clin Orthop Relat Res 469(8):2377–2384
82. Huston LJ, Vibert B, Ashton-Miller JA et al (2001) Gender differences in knee angle when landing from a drop-jump. Am J Knee Surg 14(4):215–219
83. Ikeda Y, Kijima K, Kawabata K et al (2007) Relationship between side medicine-ball throw performance and physical ability for male and female athletes. Eur J Appl Physiol 99(1):47–55
84. Ireland ML, Ballantyne BT, Little K et al (2001) A radiographic analysis of the relationship between the size and shape of the intercondylar notch and anterior cruciate ligament injury. Knee Surg Sports Traumatol Arthrosc 9(4):200–205
85. Jones MT, Matthews TD, Murray M et al (2010) Psychological correlates of performance in female athletes during a 12-week off-season strength and conditioning program. J Strength Cond Res 24(3): 619–628
86. Khan MS, Seon JK, Song EK (2011) Risk factors for anterior cruciate ligament injury: assessment of tibial plateau anatomic variables on conventional MRI using a new combined method. Int Orthop 35(8):1251–1256
87. Kinzey SJ, Armstrong CW (1998) The reliability of the star-excursion test in assessing dynamic balance. J Orthop Sports Phys Ther 27(5):356–360
88. Knapik JJ, Sharp MA, Canham-Chervak M et al (2001) Risk factors for training-related injuries among men and women in basic combat training. Med Sci Sports Exerc 33(6):946–954

89. Kraemer WJ, Patton JF, Gordon SE et al (1995) Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. J Appl Physiol 78(3):976–989
90. Krosshaug T, Nakamae A, Boden BP et al (2007) Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. Am J Sports Med 35(3):359–367
91. Krustrup P, Bangsbo J (2001) Physiological demands of top-class soccer refereeing in relation to physical capacity: effect of intense intermittent exercise training. J Sports Sci 19(11):881–891
92. Krustrup P, Mohr M, Amstrup T et al (2003) The yo-yo intermittent recovery test: physiological response, reliability, and validity. Med Sci Sports Exerc 35(4):697–705
93. Krustrup P, Mohr M, Ellingsgaard H et al (2005) Physical demands during an elite female soccer game: importance of training status. Med Sci Sports Exerc 37(7):1242–1248
94. Krustrup P, Mohr M, Nybo L et al (2006) The Yo-Yo IR2 test: physiological response, reliability, and application to elite soccer. Med Sci Sports Exerc 38(9):1666–1673
95. Leger LA, Lambert J (1982) A maximal multistage 20-m shuttle run test to predict VO_2 max. Eur J Appl Physiol Occup Physiol 49(1):1–12
96. Lidor R, Hershko Y, Bilkevitz A et al (2007) Measurement of talent in volleyball: 15-month follow-up of elite adolescent players. J Sports Med Phys Fitness 47(2):159–168
97. Lidor R, Ziv G (2010) Physical and physiological attributes of female volleyball players – a review. J Strength Cond Res 24(7):1963–1973
98. Little T, Williams AG (2005) Specificity of acceleration, maximum speed, and agility in professional soccer players. J Strength Cond Res 19(1):76–78
99. Lombardo S, Sethi PM, Starkey C (2005) Intercondylar notch stenosis is not a risk factor for anterior cruciate ligament tears in professional male basketball players: an 11-year prospective study. Am J Sports Med 33(1):29–34
100. Lund-Hanssen H, Gannon J, Engebretsen L et al (1994) Intercondylar notch width and the risk for anterior cruciate ligament rupture. A case–control study in 46 female handball players. Acta Orthop Scand 65(5):529–532
101. Magal M, Smith RT, Dyer JJ et al (2009) Seasonal variation in physical performance-related variables in male NCAA Division III soccer players. J Strength Cond Res 23(9):2555–2559
102. Malina RM, Eisenmann JC, Cumming SP et al (2004) Maturity-associated variation in the growth and functional capacities of youth football (soccer) players 13–15 years. Eur J Appl Physiol 91(5–6):555–562
103. Mansour JM, Pereira JM (1987) Quantitative functional anatomy of the lower limb with application to human gait. J Biomech 20(1):51–58
104. McGregor SJ, Hulse M, Strudwick A et al (1999) The reliability and validity of two tests of soccer skill. J Sports Sci 17:815
105. McGregor SJ, Nicholas CW, Lakomy HK et al (1999) The influence of intermittent high-intensity shuttle running and fluid ingestion on the performance of a soccer skill. J Sports Sci 17(11): 895–903
106. McLeod TC, Armstrong T, Miller M et al (2009) Balance improvements in female high school basketball players after a 6-week neuromuscular-training program. J Sport Rehabil 18(4):465–481
107. Meckel Y, Machnai O, Eliakim A (2009) Relationship among repeated sprint tests, aerobic fitness, and anaerobic fitness in elite adolescent soccer players. J Strength Cond Res 23(1):163–169
108. Meister K, Talley MC, Horodyski MB et al (1998) Caudal slope of the tibia and its relationship to noncontact injuries to the ACL. Am J Knee Surg 11(4):217–219
109. Mihalik JP, Libby JJ, Battaglini CL et al (2008) Comparing short-term complex and compound training programs on vertical jump height and power output. J Strength Cond Res 22(1):47–53
110. Mirkov D, Nedeljkovic A, Kukolj M et al (2008) Evaluation of the reliability of soccer-specific field tests. J Strength Cond Res 22(4):1046–1050
111. Mohr M, Krustrup P, Bangsbo J (2003) Match performance of high-standard soccer players with special reference to development of fatigue. J Sports Sci 21(7):519–528
112. Munro AG, Herrington LC (2010) Between-session reliability of the star excursion balance test. Phys Ther Sport 11(4):128–132
113. Myrick S (2007) Injury prevention and performance enhancement: a training program for basketball. Conn Med 71(1):5–8
114. Nassis GP, Geladas ND, Soldatos Y et al (2010) Relationship between the 20-m multistage shuttle run test and 2 soccer-specific field tests for the assessment of aerobic fitness in adult semi-professional soccer players. J Strength Cond Res 24(10):2693–2697
115. Nicks CR, Morgan DW, Fuller DK et al (2009) The influence of respiratory muscle training upon intermittent exercise performance. Int J Sports Med 30(1):16–21
116. Noyes FR, Barber SD, Mangine RE (1991) Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med 19(5):513–518
117. 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
118. Olmsted LC, Carcia CR, Hertel J et al (2002) Efficacy of the star excursion balance tests in detecting reach deficits in subjects with chronic ankle instability. J Athl Train 37(4):501–506
119. Olsen OE, Myklebust G, Engebretsen L et al (2004) Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am J Sports Med 32(4):1002–1012

120. Ostenberg A, Roos H (2000) Injury risk factors in female European football. A prospective study of 123 players during one season. Scand J Med Sci Sports 10(5):279–285
121. Pacey V, Nicholson LL, Adams RD et al (2010) Generalized joint hypermobility and risk of lower limb joint injury during sport: a systematic review with meta-analysis. Am J Sports Med 38(7): 1487–1497
122. Padua DA, Distefano LJ (2009) Sagittal plane knee biomechanics and vertical ground reaction forces are modified following ACL injury prevention programs: a systematic review. Sports Health 1(2): 165–173
123. Pauole K, Madole K, Garhammer J et al (2000) Reliability and validity of the t-test as a measure of agility, leg power, and leg speed in college-aged men and women. J Strength Cond Res 14(4):443–450
124. Plisky PJ, Rauh MJ, Kaminski TW et al (2006) Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. J Orthop Sports Phys Ther 36(12):911–919
125. Rampinini E, Impellizzeri FM, Castagna C et al (2007) Factors influencing physiological responses to small-sided soccer games. J Sports Sci 25(6): 659–666
126. Rampinini E, Sassi A, Azzalin A et al (2010) Physiological determinants of Yo-Yo intermittent recovery tests in male soccer players. Eur J Appl Physiol 108(2):401–409
127. Ramsbottom R, Brewer J, Williams C (1988) A progressive shuttle run test to estimate maximal oxygen uptake. Br J Sports Med 22(4):141–144
128. Reid A, Birmingham TB, Stratford PW et al (2007) Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. Phys Ther 87(3):337–349
129. Reiman MP, Manske RC (2009) Functional testing in human performance. Human Kinetics, Champaign
130. Ross MD, Langford B, Whelan PJ (2002) Test-retest reliability of 4 single-leg horizontal hop tests. J Strength Cond Res 16(4):617–622
131. Sabin MJ, Ebersole KT, Martindale AR et al (2010) Balance performance in male and female collegiate basketball athletes: influence of testing surface. J Strength Cond Res 24(8):2073–2078
132. Sassi RH, Dardouri W, Yahmed MH et al (2009) Relative and absolute reliability of a modified agility T-test and its relationship with vertical jump and straight sprint. J Strength Cond Res 23(6): 1644–1651
133. Schickendantz MS, Weiker GG (1993) The predictive value of radiographs in the evaluation of unilateral and bilateral anterior cruciate ligament injuries. Am J Sports Med 21(1):110–113
134. Semenick D (1990) The T test. NCSA J 12(1): 36–37
135. Serpiello FR, McKenna MJ, Stepto NK et al (2011) Performance and physiological responses to repeated-sprint exercise: a novel multiple-set approach. Eur J Appl Physiol 111(4):669–678
136. Sheehan FT, Sipprell WH 3rd, Boden BP (2012) Dynamic sagittal plane trunk control during anterior cruciate ligament injury. Am J Sports Med 40(5):1068–1074
137. Sheppard JM, Young WB, Doyle TL et al (2006) An evaluation of a new test of reactive agility and its relationship to sprint speed and change of direction speed. J Sci Med Sport 9(4):342–349
138. Siegler J, Robergs R, Weingart H (2006) The application of soccer performance testing protocols to the non-elite player. J Sports Med Phys Fitness 46(1):44–51
139. Simon RA, Everhart JS, Nagaraja HN et al (2010) A case–control study of anterior cruciate ligament volume, tibial plateau slopes and intercondylar notch dimensions in ACL-injured knees. J Biomech 43(9): 1702–1707
140. Sirotic AC, Coutts AJ (2007) Physiological and performance test correlates of prolonged, high-intensity, intermittent running performance in moderately trained women team sport athletes. J Strength Cond Res 21(1):138–144
141. Smith HC, Johnson RJ, Shultz SJ et al (2012) A prospective evaluation of the landing error scoring system (LESS) as a screening tool for anterior cruciate ligament injury risk. Am J Sports Med 40(3):521–526
142. Smith HC, Vacek P, Johnson RJ et al (2012) Risk factors for anterior cruciate ligament injury: a review of the literature – part 1: neuromuscular and anatomic risk. Sports Health 4(1):69–78
143. Souhail H, Castagna C, Mohamed HY et al (2010) Direct validity of the yo-yo intermittent recovery test in young team handball players. J Strength Cond Res 24(2):465–470
144. Stensrud S, Myklebust G, Kristianslund E et al (2011) Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. Br J Sports Med 45(7):589–595
145. Stijak L, Herzog RF, Schai P (2008) Is there an influence of the tibial slope of the lateral condyle on the ACL lesion? A case–control study. Knee Surg Sports Traumatol Arthrosc 16(2):112–117
146. Svensson M, Drust B (2005) Testing soccer players. J Sports Sci 23(6):601–618
147. Swanik CB, Covassin T, Stearne DJ et al (2007) The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. Am J Sports Med 35(6):943–948
148. Teitz CC, Lind BK, Sacks BM (1997) Symmetry of the femoral notch width index. Am J Sports Med 25(5):687–690
149. Thomas A, Dawson B, Goodman C (2006) The yo-yo test: reliability and association with a 20-m shuttle run and VO(2max). Int J Sports Physiol Perform 1(2):137–149
150. Thorpe JL, Ebersole KT (2008) Unilateral balance performance in female collegiate soccer athletes. J Strength Cond Res 22(5):1429–1433
151. Todd MS, Lalliss S, Garcia E et al (2010) The relationship between posterior tibial slope and anterior

cruciate ligament injuries. Am J Sports Med 38(1):63–67
152. Turner A, Walker S, Stembridge M et al (2011) A testing battery for the assessment of fitness in soccer players. Strength Cond J 33(5):29–39
153. Uhorchak JM, Scoville CR, Williams GN et al (2003) Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets. Am J Sports Med 31(6):831–842
154. van Eck CF, Martins CA, Lorenz SG et al (2010) Assessment of correlation between knee notch width index and the three-dimensional notch volume. Knee Surg Sports Traumatol Arthrosc 18(9):1239–1244
155. Vanderford ML, Meyers MC, Skelly WA et al (2004) Physiological and sport-specific skill response of olympic youth soccer athletes. J Strength Cond Res 18(2):334–342
156. Veale JP, Pearce AJ, Carlson JS (2010) The Yo-Yo Intermittent Recovery Test (Level 1) to discriminate elite junior Australian football players. J Sci Med Sport 13(3):329–331
157. Vescovi JD, Brown TD, Murray TM (2006) Positional characteristics of physical performance in Division I college female soccer players. J Sports Med Phys Fitness 46(2):221–226
158. Vescovi JD, McGuigan MR (2008) Relationships between sprinting, agility, and jump ability in female athletes. J Sports Sci 26(1):97–107
159. Vyas S, van Eck CF, Vyas N et al (2011) Increased medial tibial slope in teenage pediatric population with open physes and anterior cruciate ligament injuries. Knee Surg Sports Traumatol Arthrosc 19(3):372–377
160. Weston M, Helsen W, MacMahon C et al (2004) The impact of specific high-intensity training sessions on football referees' fitness levels. Am J Sports Med 32(1 Suppl):54S–61S
161. Wilk KE, Romaniello WT, Soscia SM et al (1994) The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. J Orthop Sports Phys Ther 20(2):60–73
162. Williford HN, Scharff-Olson M, Duey WJ et al (1999) Physiological status and prediction of cardiovascular fitness in highly trained youth soccer athletes. J Strength Cond Res 13(1):10–15
163. Willson JD, Ireland ML, Davis I (2006) Core strength and lower extremity alignment during single leg squats. Med Sci Sports Exerc 38(5):945–952
164. Wynne-Davies R (1970) Acetabular dysplasia and familial joint laxity: two etiological factors in congenital dislocation of the hip. A review of 589 patients and their families. J Bone Joint Surg Br 52(4):704–716
165. Young W, MacDonald C, Heggen T et al (1997) An evaluation of the specificity, validity and reliability of jumping tests. J Sports Med Phys Fitness 37(4):240–245
166. Young WB, Newton RU, Doyle TL et al (2005) Physiological and anthropometric characteristics of starters and non-starters and playing positions in elite Australian Rules Football: a case study. J Sci Med Sport 8(3):333–345
167. Zeller BL, McCrory JL, Kibler WB et al (2003) Differences in kinematics and electromyographic activity between men and women during the single-legged squat. Am J Sports Med 31(3):449–456
168. Ziv G, Lidor R (2010) Vertical jump in female and male basketball players – a review of observational and experimental studies. J Sci Med Sport 13(3):332–339

Part IV

ACL Injury Prevention Programs

Sportsmetrics ACL Intervention Training Program: Components, Results

14

Frank R. Noyes and Sue D. Barber-Westin

Contents

F.R. Noyes, M.D.
Cincinnati Sportsmedicine and Orthopaedic Center, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

S.D. Barber-Westin, B.S. (✉)
Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA
e-mail: sbwestin@csmref.org

Introduction, Historical Background

The Sportsmetrics training program represents the first knee ligament intervention program for female athletes to be published in the peer-reviewed orthopedic literature. Multiple studies have been conducted to scientifically justify the program's ability to reduce the incidence of non-contact anterior cruciate ligament (ACL) injuries, improve deficiencies in neuromuscular indices, and enhance athletic performance indices. 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. The authors 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 females 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 specially designed plyometric training program could change these landing mechanics and improve hamstrings strength.

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_14, © Springer-Verlag Berlin Heidelberg 2012

An intervention program was created that focused 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 initial program implemented these concepts along with strength training (lower extremity, upper extremity, and core) and flexibility [7]. 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 scientifically if Sportsmetrics training could alter the kinematics and kinetics of the knee and lower extremity and reduce the incidence of knee ligament injuries in female athletes [8]. Later studies also examined the effectiveness of sports-specific training programs on improving athletic performance indicators such as speed, agility, and aerobic conditioning [3, 12, 13].

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' research foundation 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. 15 were created at the nonprofit 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:

- Sue Barber-Westin
- Michelle Brock
- Thomas Campbell
- Amy Dudley
- Cassie Fleckenstein
- Kevin Ford
- Timothy Hewett
- Ann Hollenbeck
- Gregory Myer
- Thomas Nance
- Frank R. Noyes, MD
- Jennifer Riccobenne
- Amanda Stroupe
- Stephanie T. Smith
- Catherine Walsh
- John West

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, flexibility.
- Conduct preseason or off-season.
- Three days/week for 6 weeks.
- Original program and sports-specific programs available.

Components

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.

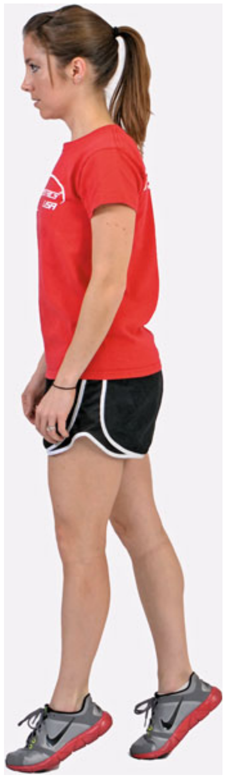


Fig. 14.1 Toe walk

Fig. 14.3 Straight leg march

Fig. 14.2 Heel walk

Toe Walk

Walk on the toes and keep the legs straight (Fig. 14.1). Do not allow the heel to touch the ground. Keep the hips neutral during the entire exercise.

Heel Walk

Walk on the heels and keep the legs straight (Fig. 14.2). 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.

Straight Leg March

Walk with both legs straight, alternating lifting up each leg as high as possible without compromising form (Fig. 14.3). Keep the knees straight and the posture erect. Do not lean backward.

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. 14.4). 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.

Fig. 14.4 Leg cradle

Dog and Bush (Hip Rotator) Walk

Pretend there is an obstacle directly in front of you. Face forward and keep the shoulders and hips square. Extend one leg at the hip and keep the knee bent (Fig. 14.5). Rotate the leg out at the hip and bend the knee to 90°. Rotate and bring the leg up and over the obstacle, then place it back on the ground. Repeat with the opposite leg.

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

Fig. 14.5 (**a**, **b**) Dog and bush walk

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.

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.

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.

Stride Out

Begin jogging forward using an exaggerated running form. Drive the knees as high as possible and kick the feet back, as if trying to make a large complete circle with the legs. Stay up on the balls of the feet throughout the exercise.

All-Out Sprint

Sprint forward as fast as possible, making sure to maintain proper technique and running form.

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 [5, 15]. However, if done improperly, plyometrics are not 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 multidirectional, 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 14.1).

Table 14.1 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

Phase 1 (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 knees are critical components to

Fig. 14.6 (**a**, **b**) Tuck jump

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 2 (fundamentals phase) continues emphasis on proper techniques. Athletes continue to perform six of the jumps from phase 1, but for longer periods of time. In addition, three new jumps are incorporated. Phase 3 (performance phase) increases the quantity and speed of the jumps to develop a truly plyometric exercise routine. The athlete completes as many jumps as possible with proper form and is encouraged to focus on the height achieved in each jump.

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 straightforward.

Common Problems: Slouched posture, excessive knee flexion, head down, eyes watching the feet.

Corrections: Keep the eyes and head focused up, keep the knees slightly bent, land softly.

Tuck Jump

Instruction: Begin standing with the feet shoulder-width apart. Jump up and bend the knees upward together up toward the chest as high as possible (Fig. 14.6). Land softly with the knees slightly flexed and feet shoulder-width apart.

Fig. 14.7 (**a**, **b**) Squat jump

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, the back should be straight, and the eyes looking up.

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 (Fig. 14.7). 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.

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, keep the back straight, and the head and eyes up.

Barrier Jump Side-to-Side

Instruction: A cone or barrier approximately 6–8″ (15.24–20.32 cm) in height is placed on a hard surface. Start upright with the knees deeply flexed (Fig. 14.8) 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.

Common Problems: Starting or landing with stiff, straight, or wobbly knees; not bringing the entire body over the barrier; double-bouncing on 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.

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.

180° Jump

Instruction: Begin with the knees slightly flexed and the feet shoulder-width apart. Jump straight up and turn 180° in midair before landing (Fig. 14.9). Hold the landing for 2 seconds, and then reverse the direction and repeat the 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 1 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.

Fig. 14.8 (**a**–**c**) Barrier jump side-to-side

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.

Broad Jump

Instruction: Begin with the knees deeply flexed, then jump forward as far as possible, taking off and landing on both feet at the same time. Land softly in the same deeply crouched position, hold for 5 s, and then repeat the jump.

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.

Bounding in Place

Instruction: Begin by standing on one leg with the knee slightly flexed, eyes looking straight ahead, and the opposite leg bent behind the body. Staying in one place, alternate the leg positions by driving the back leg forward and upward (Fig. 14.10). 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.

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 is used for the final landing, which is held for 5 s.

Fig. 14.9 (**a**–**c**) 180° jump

Fig. 14.10 (**a**–**c**) Bounding in place

Fig. 14.10 (continued)

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.

Barrier Hop Side-to-Side, Single Leg

Using the same cone or barrier from phase 1, a single-leg hop side-to-side over the barrier is performed.

Barrier Hop Forward-Backward, Single Leg

Using the same cone or barrier from phase 1, a single-leg hop forward and backward over the barrier is performed (Fig. 14.11).

Scissor Jump

Instruction: Begin in a lunge position with the front knee bent directly over the ankle. Push off with the front leg, jump straight up in the air (Fig. 14.12), 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 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.

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.

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.

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.

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

Fig. 14.11 (**a**–**c**) Barrier hop forward-backward

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.

Mattress Jump Side-to-Side

Instructions: A cone or barrier is placed on a cushioned surface approximately 2–3″ (5.08–7.62 cm) deep. Jump from one side to the other over the barrier (Fig. 14.13).

Common Problems: Landing with unstable knees or knees collapsed inward, double-bouncing on landing, and landing with feet staggered.

Corrections: Take off and land with both feet parallel and together, and control the landing to be able to immediately take off back over the barrier.

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.

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.

Jump into Bounding

Jump forward off both feet, land on one leg with the other bent behind, and immediately begin

Fig. 14.12 (**a**–**c**) Scissor jump

bounding for distance. The common problems and corrections are those described for the bounding for distance hop.

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 1 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 pulldown, 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.

Mini-squats with Resistance Band

Instructions: Stand on the center of a strip of resistance band with the feet shoulder-width apart (Fig. 14.14) 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

Fig. 14.13 (**a**–**c**) Mattress jump side-to-side

Fig. 14.14 (**a**, **b**) Mini-squat with resistance band

Fig. 14.15 Lunge

ankles. Push through the heels and rise up to the starting position. Perform for 30 s during weeks 1–3 and 60 s during weeks 4–6.

Common Problems: Forward shift of the body or knees, using a slouched posture, and maintaining too much slack in the band.

Corrections: Wiggle the toes throughout the exercise, keep the back straight, the head up with eyes looking forward, and the knees centered over the ankles.

Walking Lunges Forward

From a standing position, step out with one leg as far as possible. Bend the knees and lower the back leg toward the ground, stopping just before the knee touches the ground (Fig. 14.15). 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.

Prone Hamstrings with Partner Resistance

Instructions: The athlete performing the exercise lies flat on a mat on their stomach with the abdominal and gluteus muscles tightened to press the hips into the floor. A partner uses their hands to place pressure on the lower calf which the athlete resists, bending at the knee so 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.

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.

Supine Hamstring Bridge

Instructions: Lie flat on the back, bend one knee, and place the heel of the foot as close to the gluteus as possible. Extend the other leg straight up into the air (Fig. 14.16). 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.

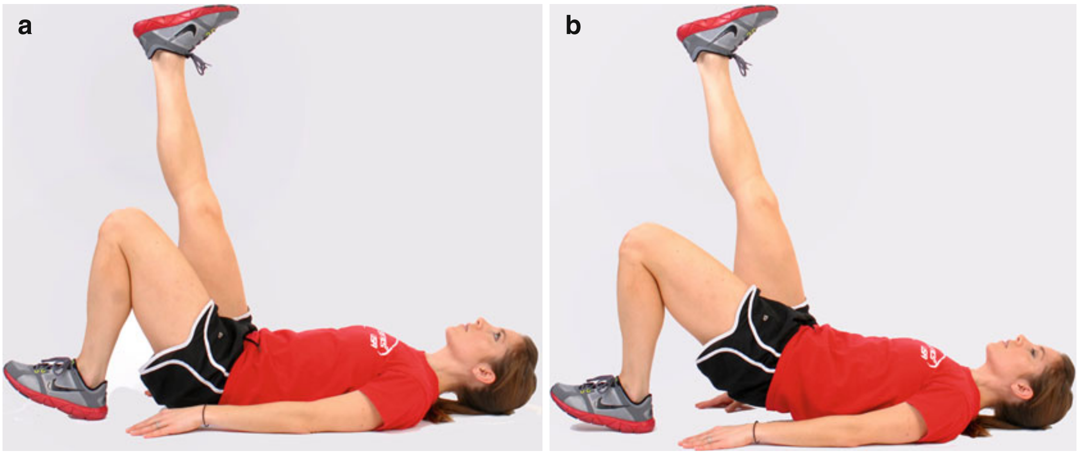


Fig. 14.16 (**a**, **b**) Supine hamstrings bridge

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.

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.

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.

Arm Swing with Resistance Band

Instructions: Stand on the center of a strip of resistance band with the feet shoulder-width apart and grip each end of the band. Pull the resistance band to waist level so that the band is tight and the elbows are at a 90° angle (Fig. 14.17). 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.

Superman (Alternating Arms/Legs)

Instructions: Lie face down and place the forehead on top of the back of one hand. Extend the other arm out on the ground. Tighten the abdominal muscles and raise the upper body in order to lift the extended arm. Simultaneously, raise the leg opposite from the extended arm using the hip and gluteals (Fig. 14.18). 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.

Fig. 14.17 (**a**, **b**) Arm swing with resistance band

Fig. 14.18 (**a**, **b**) Abdominals (superman)

Abdominals (Russian Twists)

Instructions: Lie on the ground, bend the knees, and place the heels on the floor. Raise the upper body up to a 45° angle by bending at the hips and not the waist. Maintain this position and move the trunk as a unit to rotate the upper body side-to-side. Touch the ground with the hands next to the hip with each rotation (Fig. 14.19). 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. Move the torso as a unit and touch the ground with the hands with each rotation.

Abdominals (Plank)

Instructions: Lie facedown and position the elbows under the shoulders with the forearms on the floor (Fig. 14.20). 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.

Fig. 14.19 (**a**, **b**) Abdominals (Russian twists)

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. 14.21). 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 shoulders are not kept off of the ground, the upper body rotates, and the legs are moved close to the body.

Corrections: Lift the upper body up from the waist, keep the elbows open and upper body stationary, and take the legs through a full cycle close to the ground.

Hip Flexor Resistance Band Kicking

Instructions: Place one end of a piece of resistance band around the ankle and the other end around a stationary object. Stand with the back to the stationary object and then step forward with the free leg to produce moderate tension in the band, producing approximately 15° of hip extension in the leg with the resistance band (Fig. 14.22). Then, drive the knee up and forward with maximal effort against the resistance of the band until the thigh is parallel with the ground. Return the leg to a slightly extended position after each exertion. Perform two sets of 10 repetitions, with 30 s of rest between each set. A third set of 20 repetitions is done in phase 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.

Fig. 14.20 Abdominals (plank)

Fig. 14.21 (**a**, **b**) Abdominals (bicycle kicks)

Fig. 14.22 (**a**, **b**) Hip flexor resistance band kicking

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.

Steamboats (Hip Flexion)

Instructions: This exercise may be done in place of hip flexor resistance band kicking. Place a resistance band just above the ankles (Fig. 14.23). 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 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.

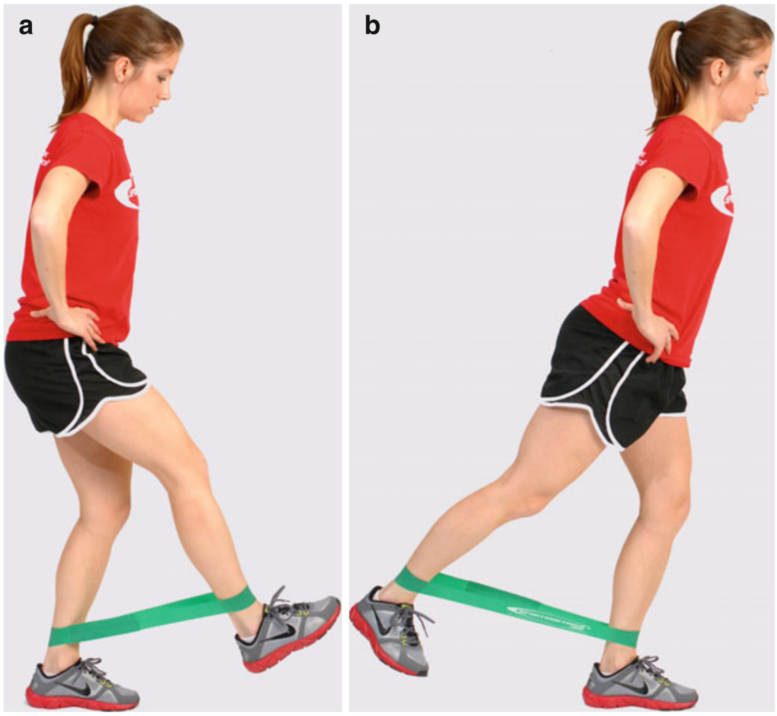


Fig. 14.23 (**a**, **b**) Steamboats

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.

Hip Abductor Resistance Band Kicking

Instructions: Place one end of a piece of resistance band around the ankle and the other end around a stationary object. Stand sideways so that the leg with the resistance is furthest away from the object (Fig. 14.24). Step far enough to produce moderate tension in the band and then kick the outside leg sideways against the resistance of the band. Perform two sets of 10 repetitions, with 30 s of rest between sets. A third set of 20 repetitions is done in phase 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.

Lateral Walking with Resistance Band

Instructions: This exercise may replace hip abduction resistance band kicking. A resistance band is positioned just above the ankles (Fig. 14.25). Begin with the feet shoulder-width apart. Step out with one foot 2–3 ft 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 to come together between steps, snapping the leg that follows back to the starting position, keeping the knees locked, bending forward at the waist, rounding the shoulders, and looking down at the ground.

Corrections: Keep the back and shoulders straight and the head and eyes up. Use a comfortable distance between steps that permits leg control throughout the exercise and keep the walking motion slow and under control at all times.

Fig. 14.24 (**a**, **b**) Hip abductor resistance band kicking

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.

Hamstrings

Instructions: Sit on the floor and extend the right leg fully. Bend the left knee and place the inside of the foot along the left calf (Fig. 14.26). Keep the back straight and slowly reach with both hands toward the toes. Place the hands on the floor along side of the legs or hold onto the toes.

Common Problems: The shoulders are rounded when leaning into the stretch, the head drops and the chin rests on the chest, and the knee of the leg on the ground bends.

Corrections: Keep the back straight when leaning forward, bend forward at the waist, and keep the shoulders back and head up.

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. 14.27). This stretch may be done lying on the back to support the spine and neck.

Quadriceps

Instructions: From a standing position, grab a foot or ankle and lift it up behind the body. Gently

Fig. 14.25 (**a**, **b**) Lateral walking with resistance band

Fig. 14.26 Hamstrings stretch

Fig. 14.27 Iliotibial band stretch

pull the lower leg and foot up, directly behind the upper leg. Do not twist inward or outward (Fig. 14.28).

Common Problems: Resting the foot on the buttocks, pulling the leg and/or foot inward or outward, and locking the knee of the leg used for balance.

Corrections: Pull the foot straight up, keep the back straight, the shoulders back, and the head up.

Fig. 14.28 Quadriceps stretch

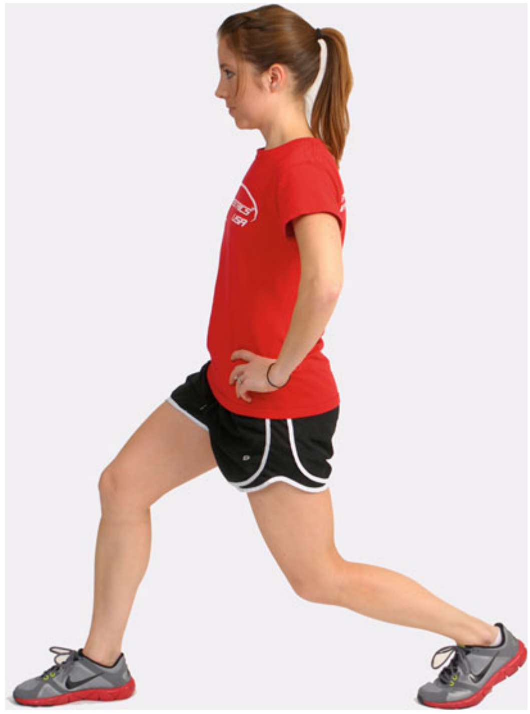


Fig. 14.29 Hip flexor stretch

Hip Flexor

Instructions: Begin in a lunge position with the front knee slightly bent (Fig. 14.29). 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. 14.30 Gastrocnemius stretch

Gastrocnemius

Instructions: Begin in a long lunge position with the front knee slightly bent, but not extended past the ankle (Fig. 14.30). 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.

Fig. 14.31 Deltoid stretch

Corrections: Keep the back leg straight and the heel on the ground. Keep the back straight, the shoulders back, and head up.

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.

Deltoid

While either standing or sitting, bring the left arm across the body, placing the elbow close to the chest. Clasp the arm at the elbow and gently press into and across the body (Fig. 14.31). Keep the shoulders relaxed and the head and neck neutral.

Triceps, Latissimus Dorsi

While either standing or sitting, extend the right arm above the head. Bend the elbow behind the head and bring the palm of the hand toward the center of the upper back. Grasp the elbow with the left hand and gently press down and back (Fig. 14.32).

Fig. 14.32 (**a**, **b**) Triceps, latissimus dorsi stretch

Pectoralis, Biceps

While standing, clasp the hands behind the back. With the shoulders and neck relaxed, extend the elbows. Keep the chest open and lift the hands up. The posture stays upright and neutral, and the knees slightly flexed (Fig. 14.33).

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

Fig. 14.33 Pectoralis, biceps stretch

Fig. 14.34 Low back stretch

resting on the floor. Gradually move the hands further away from the body. Do not rise up from the heels (Fig. 14.34).

Critical Points

- Dynamic warm-up: ten exercises to prepare the body for rigorous training
- Plyometric/jump training philosophy is to teach correct jumping and landing techniques throughout 6 weeks of training:
  - Three phases: technique development, fundamentals, performance
  - Constant verbal cues, feedback
  - Seven to nine jumps per session
- Strength training for upper extremity (deltoids, pectorals, triceps, latissimus dorsi/low back), lower extremity (quadriceps, hamstrings, 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

Research Investigations

Changes in Neuromuscular Indices

It is well recognized that differences exist between female and male athletes in movement patterns during athletic tasks; muscle strength, activation, and recruitment patterns; and knee joint stiffness under controlled, preplanned, and reactive conditions in the laboratory. Many investigators believe that these neuromuscular and biomechanical factors are at least partially responsible for the disparity between genders in noncontact ACL injury rates. Studies conducted at the authors' laboratory and those of others have demonstrated that the Sportsmetrics program is effective in inducing desired changes in neuromuscular indices in female athletes. These include reduced deleterious abduction and adduction moments [7], lowered peak landing forces [7], increased isokinetic hamstrings strength and improved hamstrings/quadriceps ratio [7, 11, 16], and improved overall lower limb alignment in the coronal plane on a drop-jump test [4, 11–14]. See also Chap. 18 for further details on these findings.

Reduction in Peak Landing Forces, Abduction and Adduction Moments

A laboratory study was conducted at the authors' center in 11 high school female volleyball players to determine the effect of Sportsmetrics training on landing mechanics and lower extremity strength [7]. A control group of nine male subjects was matched with the females for height, weight, and age. The female athletes underwent a series of tests before and after 6 weeks of Sportsmetrics training that included vertical jump height, isokinetic muscle assessment 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 volleyball block jump by 22 % ($P = 0.006$) or an average of 456 N (103 lb). All but one of the female subjects showed a decrease in these forces (Table 14.2 and Fig. 14.35) [7]. Knee abduction and adduction moments decreased approximately 50 % (Fig. 14.36). Trained female athletes had lower peak landing forces than male athletes and lower adduction and abduction moments after training compared to pre-training values. Decreased abduction or adduction moments may lessen the risk of lift-off of the medial or lateral femoral condyle, improve tibiofemoral contact stabilizing forces [9], and reduce the risk of a knee ligament injury.

Increased Hamstring Muscle Strength and Hamstrings/Quadriceps Ratio

Significant increases in isokinetic knee flexion peak torque following Sportsmetrics training were reported in three investigations (Table 14.2) [7, 11, 16]. In 1 study involving female high school volleyball players [7], hamstring muscle power increased 44 % on the dominant side and 21 % on the nondominant side. In a group of 11 collegiate female basketball players, isokinetic knee flexion peak torque values of the dominant leg significantly improved ($P = 0.008$) [16]. In 62 female high school athletes, significant improvements were measured in both the dominant and nondominant legs ($P < 0.0001$). In addition, the hamstring-to-quadriceps muscle peak torque ratio significantly improved following Sportsmetrics training in two studies, correcting muscular imbalances [7, 11].

Improved Overall Lower Limb Alignment on Drop-Jump Test

Sportsmetrics training has effectively improved overall lower limb alignment in the coronal plane in several investigations [11–14]. Statistically significant improvements were found in the absolute (Table 14.2) and normalized knee and ankle separation distances for all phases (pre-land, land, takeoff) of the jump-land sequence ($P < 0.001$). Figure 14.37 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 [4], 16 competitive, experienced 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 which 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. 14.38). 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. 14.39). 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

Table 14.2 Significant improvements from Sportsmetrics training on neuromuscular indices in female athletes

Number athletes trained, study citation	Factor	Pre-train Mean ± SD	Post-train Mean ± SD	*P* value
11 High school volleyball [7]	Peak landing forces (× body weight)	4.2	3.4	<0.01
	Abduction moment (% body weight × height)	4.0	1.9	<0.05
	Adduction moment (% body weight × height)	3.4	2.1	<0.05
	Knee flexion peak torque			
11 High school volleyball [7]	Nondominant leg (360°/s, Nm)	37 ± 7	46 ± 8	<0.01
11 Collegiate basketball [16]	Dominant leg (60°/s, Nm)	91 ± 18	101 ± 22	0.008
62 High school athletes [11]	Dominant leg (300°/s, Nm/body weight)	40 ± 8	44 ± 7	<0.0001
	Nondominant leg (300°/s, Nm/body weight)	38 ± 8	42 ± 8	<0.0001
	Hamstrings/quadriceps ratio			
11 High school volleyball [7]	Dominant leg (360°/s)	55 ± 9	62 ± 7	<0.05
	Nondominant leg (360°/s)	47 ± 8	59 ± 9	<0.01
62 High school athletes [11]	Nondominant leg (300°/s)	73 ± 15	83 ± 15	0.001
	Lower limb alignment drop-jump test			
62 High school athletes [11]	Absolute knee separation distance (cm)	23 ± 9	29 ± 8	<0.001
	Normalized knee separation distance (%)	51 ± 19	68 ± 18	<0.001
34 High school volleyball [12]	Absolute knee separation distance (cm)	21 ± 8	26 ± 5	0.002
	Normalized knee separation distance (%)	56 ± 19	63 ± 13	0.04
57 High school basketball [13]	Absolute knee separation distance (cm)	18 ± 7	32 ± 10	<0.0001
	Normalized knee separation distance (%)	45 ± 17	74 ± 19	<0.0001
62 High school soccer [14]	Absolute knee separation distance (cm)	15 ± 4	23 ± 6	<0.0001
	Normalized knee separation distance (%)	36 ± 7	54 ± 14	<0.0001

allowance of their volleyball training and season participation.

ACL Injury Reduction

In order to determine if Sportsmetrics training would reduce the incidence of noncontact ACL injuries in female athletes, a controlled prospective investigation was conducted in 1,263 high school soccer, volleyball, and basketball athletes [8]. There were three groups studied: 366 females from 15 teams 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

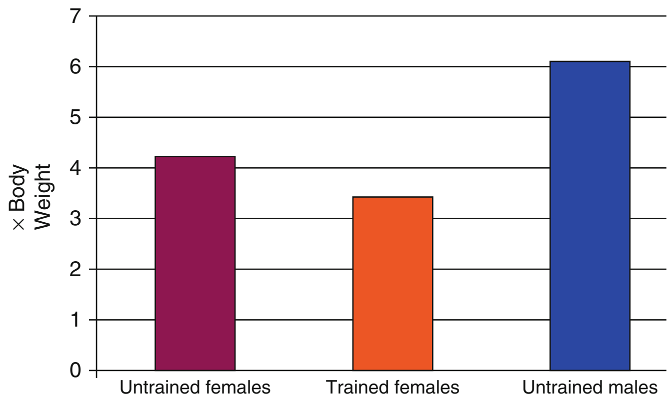


Fig. 14.35 Peak landing forces in 11 female subjects before and after Sportsmetrics training and in 9 male control subjects. There was a significant difference between untrained females and trained females and between males and both female groups ($P<0.01$) [7]

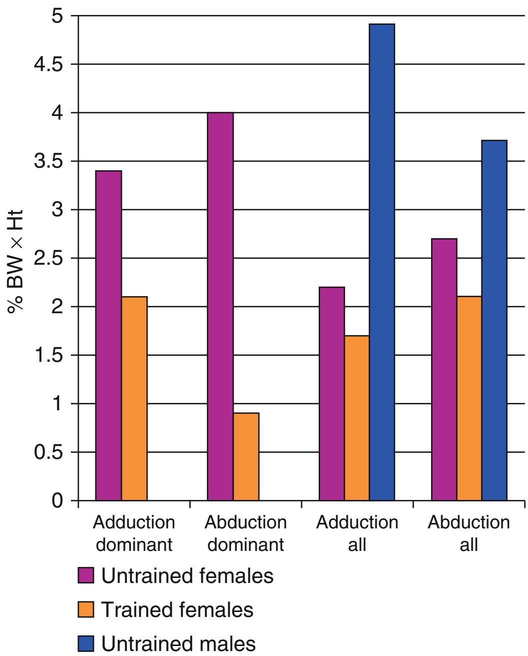


Fig. 14.36 Peak knee adduction and abduction moments on landing from a vertical jump. The 22 female subjects were grouped according to the dominant moment (adduction or abduction) and were also grouped together (All). In the dominant subgroups, the trained females had significantly smaller adduction and abduction moments compared to the untrained females ($P<0.05$). Peak abduction and adduction moments were significantly greater in the male subjects than those in the trained female subjects ($P<0.05$) [7]

undergo training. All athletes were followed throughout a single season for injuries. Weekly reports submitted by certified athletic trainers included the number of practice and competition exposures and mechanism of injury. All ACL injuries were confirmed by arthroscopy and medial collateral ligament injuries confirmed by manual valgus testing.

The total numbers of athlete exposures were 17,222 for the trained group, 23,138 for the female control group, and 21,390 for the male control group. There were 14 serious knee ligament injuries which were sustained in 2 of 366 trained female athletes (0 noncontact), 10 of 463 female control athletes (8 noncontact), and 2 of 434 male control athletes (1 noncontact). The knee injury incidence per 1,000 athlete exposures was 0.12 in trained female athletes, 0.43 in female control athletes, and 0.09 in male control athletes ($P=0.02$). Untrained female athletes had a 3.6 times higher incidence of knee injury than trained female athletes ($P=0.05$) and a 4.8 times higher incidence than male control athletes ($P=0.03$). There was no difference in the incidence of knee injury between trained female athletes and male control athletes.

The relative noncontact knee ligament injury incidence per 1,000 athlete exposures was 0 in the trained group, 0.35 in the female control group, and 0.05 in the male control group. There were five noncontact knee ligament injuries in the female control group and one in the male control group. A significant difference was found between the trained and untrained groups ($P=0.05$).

All of the knee ligament injuries occurred in basketball and soccer. The numbers of player exposures in these two sports were 9,284 for the trained female group, 19,387 for the female control group, and 21,552 for the male control group. The relative incidence of injury in the female

Fig. 14.37 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 et al. [11]. With permission from SAGE Publications, Inc.)

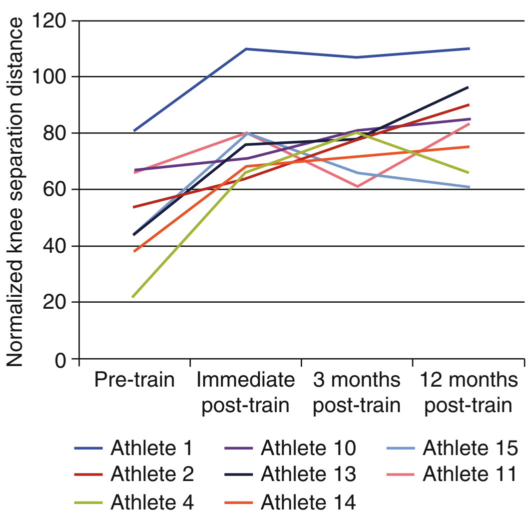


Fig. 14.38 Eight athletes who demonstrated improvements in normalized knee separation distance values at all time periods compared to the pre-train values (Reprinted with permission from Barber-Westin et al. [4])

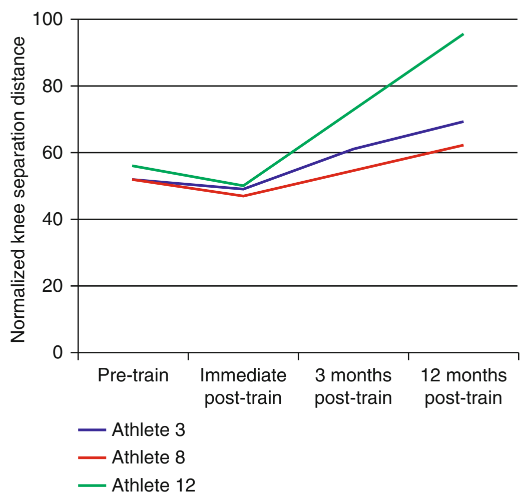


Fig. 14.39 Three athletes who had smaller normalized knee separation distance values at the immediate post-trained test compared to the pre-trained test, but who then improved at the 3- and 12-month post-trained tests (Reprinted with permission from Barber-Westin et al. [4])

control group was 2.4 times higher than that in the trained group and 5.8 times higher than the incidence in the male control group. There were significant differences in the rate of noncontact knee ligament injuries between the trained and control female groups ($P = 0.05$).

In soccer, the study involved 4,517 player exposures for the trained female group, 9,017 for the female control group, and 8,513 for the male control group. There were five serious knee ligament injuries in the female control group and one in the male control group. The relative incidence of injury was 0 in the trained female group, 0.56 in the female control group, and 0.12 in the male control group. There was a trend toward a difference in noncontact injury rates between groups, but this was not statistically significant.

In basketball, the number of player exposures was 4,767 for the trained female group, 10,370 for the female control group, and 13,039 for the male control group. Five serious knee ligament injuries occurred in the female control group, two in the trained female group, and one in the male control group. The incidence of injury was 0.42 for the trained female group, 0.48 for the female control group, and 0.08 for the male control group. Untrained female players had significantly more noncontact knee ligament injuries than did the male players ($P = 0.03$).

Internal surveillance monitoring of this program continued upon completion of this study. Over a 3-year period (2008–2011), 272 female athletes involved in high school soccer, volleyball, field hockey, basketball, softball, and lacrosse underwent supervised Sportsmetrics training in Cincinnati before the start of their sports season. The athletes were then followed for the season for injuries. During the same time period, a control group of 590 athletes were also tracked throughout the season for injuries. The exposure hours were 15,776 in the trained group and 34,220 in the control group. One noncontact ACL injury occurred in the trained group and five occurred in the control group. The monitoring program continues in a prospective manner.

Gender Disparity Investigations

The authors measured differences between genders and the effect of Sportsmetrics training on lower limb alignment on a drop-jump test (Table 14.3) [11]. The study involved 325 untrained females, 62 trained females, and 130 untrained males aged 11–19 years. The results of the video drop-jump test revealed no significant difference existed between untrained females and males for knee and ankle separation distance on landing. A marked decrease in knee separation distance (≤60 %), or a valgus alignment appearance (Fig. 14.40), 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. 14.41).

The authors 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 [1]. 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.

The authors 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 during a drop-jump test, and lower limb symmetry during single-leg hop tests [2]. The study involved 916

Table 14.3 Conclusions from the authors' gender comparison studies

Study	Factor, no. athletes tested, age	Effect of gender	Effect of age	Conclusions
Noyes and Barber-Westin [10] and Barber-Westin et al. [2]	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: no effect knee separation distance, ankle separation distance greater 9–12 years than 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 a drop-jump
Barber-Westin et al. [2]	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 et al. [2]	Hamstrings/quadriceps ratio 853 untrained females 177 untrained males Aged 9–17 years	No effect	Females: nonsignificant decline with age Males: significant decline from 9 to 14 years	Significant improvements nondominant leg only
Barber-Westin et al. [2]	Limb symmetry single-leg-timed side hop, crossover 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 crossover 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 and Barber-Westin [10]	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 %

Fig. 14.40 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 et al. [11]. With permission from SAGE Publications, Inc.)

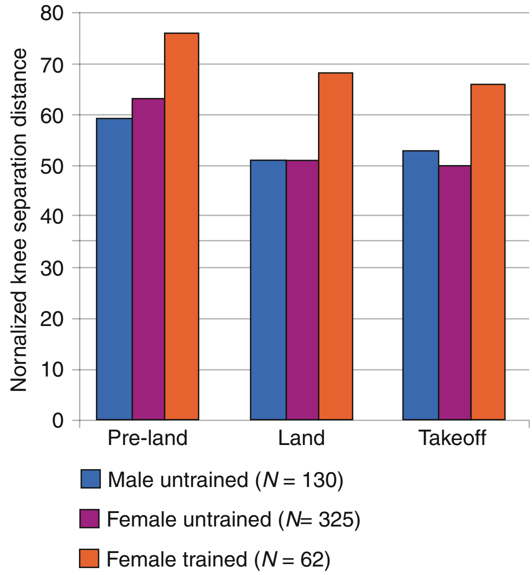


Fig. 14.41 The mean normalized knee separation distances for the three phases of the drop-jump test are shown for the male athletes, untrained female athletes, and trained female athletes. After training, female athletes had statistically significant increases in the mean normalized knee separation distance 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 et al. [11]. With permission from SAGE Publications, Inc.)

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. 14.42). Although maximum flexion strength occurred in males at age 14 ($P<0.001$), females had only slight increases from ages 9–11 (Fig. 14.43). 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. 14.44) 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. The absence of a gender difference in lower limb alignment on landing suggests other factors may be responsible for the gender disparity in knee ligament injury rates.

The authors examined age- and sex-associated development of isokinetic tibial rotation strength in 94 athletes (47 females and 47 males) aged 11–17 years [10]. There is a paucity of data regarding the internal rotation (IR) and external rotation (ER) isokinetic strength of the hamstring musculature, and whether age-related or gender-related effects exist are unknown. The study involved the measurement of IR and ER peak torques and time to peak torque at 120° 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° [6]. The results revealed that males 14–17 years of age had

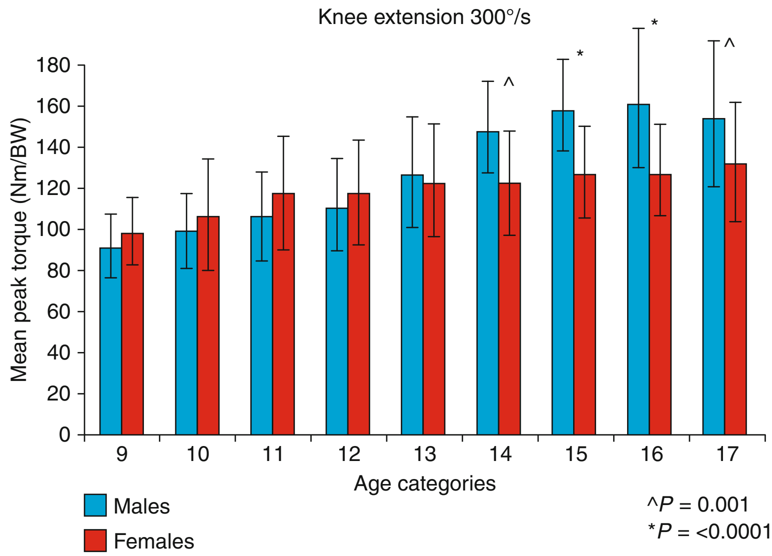


Fig. 14.42 No significant difference was found in the mean extensor peak torque ratio values between females and males in the 9- to 13-year-old age groups. However, from the ages of 14–17, males had significantly greater mean extensor peak torque ratio values than females (From Barber-Westin et al. [2]. With permission from SAGE Publications, Inc.)

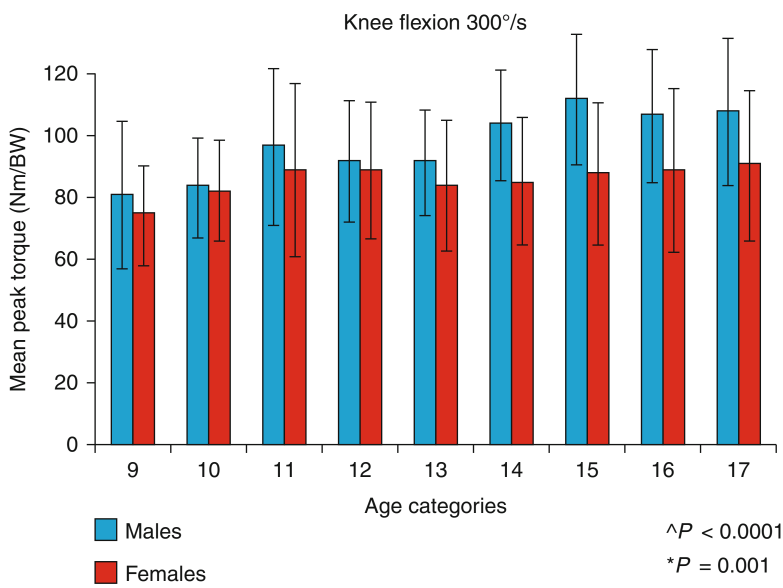


Fig. 14.43 No significant difference was found in the mean flexor peak torque ratio values between females and males in the 9- to 13-year-old age groups. However, from the ages of 14–17, males had significantly greater mean flexor peak torque ratio values than females (From Barber-Westin et al. [2]. With permission from SAGE Publications, Inc.)

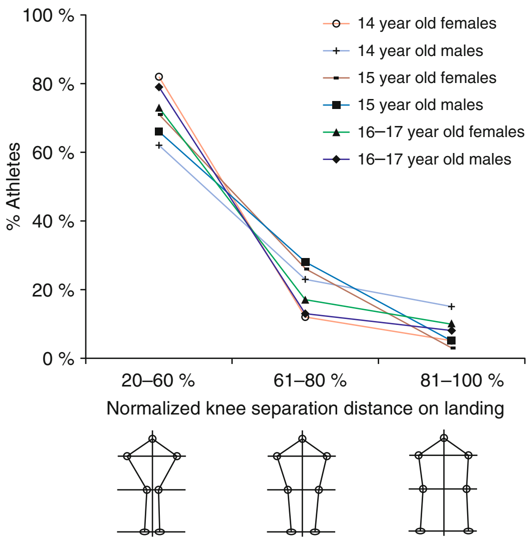


Fig. 14.44 There was no significant difference between either the male or female athletes aged 14–17 in the percent of subjects with <60 %, 61–80 %, or >80 % normalized knee separation distance. The stick figures are representative of the knee separation distance, but not of the ankle separation distance (From Barber-Westin et al. [2]. With permission from SAGE Publications, Inc.)

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 an 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. 14.45). Differences in IR peak torque and time to IR peak torque between young male and female athletes have not been previously reported.

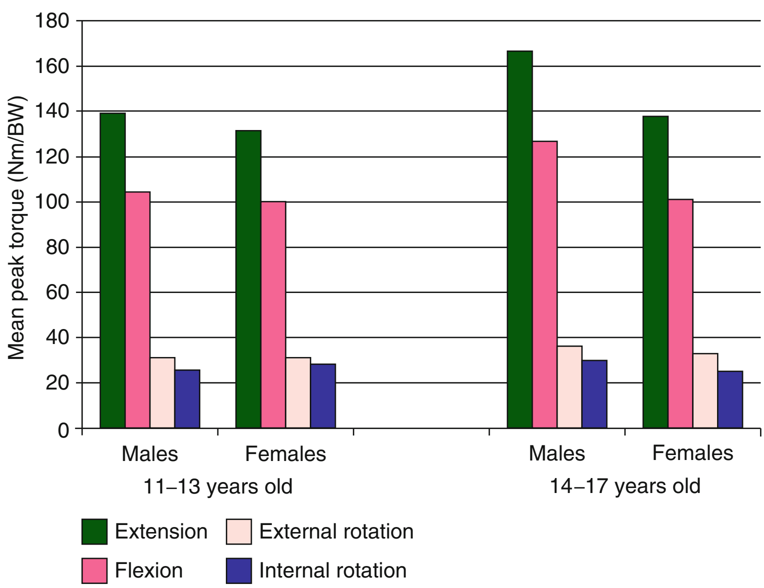


Fig. 14.45 Overall isokinetic peak torque averages for knee extensor, flexor, external rotation, and internal rotation for the dominant limb at 180°/s. A hierarchy of isokinetic muscle strength about the knee can be seen, which is similar between genders and age groups (From Noyes and Barber-Westin [10]. With permission from IOS Press)

Critical Points

- Sportsmetrics effective in inducing changes in neuromuscular indices in female athletes:
  - Reduced deleterious abduction and adduction moments, lowered peak landing forces
  - Increased isokinetic hamstrings strength
  - Improved hamstrings/quadriceps ratio, overall lower limb alignment in the coronal plane on a drop-jump test
- Sportsmetrics significantly reduced noncontact ACL injury rate in soccer and basketball players.
- 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.
  - 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.

References

1. Barber-Westin SD, Galloway M, Noyes FR et al (2005) Assessment of lower limb neuromuscular control in prepubescent athletes. Am J Sports Med 33(12): 1853–1860
2. Barber-Westin SD, Noyes FR, Galloway M (2006) Jump-land characteristics and muscle strength development in young athletes: a gender comparison of 1140 athletes 9 to 17 years of age. Am J Sports Med 34(3):375–384
3. Barber-Westin SD, Hermeto AA, Noyes FR (2010) A 6-week neuromuscular training program for competitive junior tennis players. J Strength Cond Res 24(9): 2372–2382
4. Barber-Westin SD, Smith ST, Campbell T et al (2010) The drop-jump video screening test: retention of improvement in neuromuscular control in female volleyball players. J Strength Cond Res 24(11):3055–3062
5. Chu DA (2001) Explosive power. In: Foran B (ed) High-performance sports conditioning. Human Kinetics, Champaign, pp 83–98
6. Hester JT, Falkel J (1984) Isokinetic evaluation of tibial rotation: assessment of a stabilization technique. J Orthop Sports Phys Ther 6(1):46–51
7. Hewett TE, Stroupe AL, Nance TA et al (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24(6):765–773
8. Hewett TE, Lindenfeld TN, Riccobene JV et al (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27(6):699–706
9. Markolf KL, Burchfield DM, Shapiro MM et al (1995) Combined knee loading states that generate high anterior cruciate ligament forces. J Orthop Res 13(6): 930–935
10. Noyes FR, Barber-Westin SD (2005) Isokinetic profile and differences in tibial rotation strength between male and female athletes 11 to 17 years of age. Isok Exer Sci 13:251–259
11. 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
12. Noyes FR, Barber-Westin SD, Smith ST et al (2011) A training program to improve neuromuscular indices in female high school volleyball players. J Strength Cond Res 25(8):2151–2160
13. Noyes FR, Barber-Westin SD, Smith ST et al (2012) A training program to improve neuromuscular and performance indices in female high school basketball players. J Strength Cond Res 26(3):709–719
14. Noyes FR, Barber-Westin SD, Tutalo Smith S et al (2012) A Training Program to Improve Neuromuscular and Performance Indices in Female High School Soccer Players. J Strength Cond Res. Epub ahead of print April 3, 2012. doi: 10.1519/JSC.0b013e31825423d9
15. Rimmer E, Sleivert G (2000) Effects of a plyometric intervention program on sprint performance. J Strength Cond Res 14(3):295–301
16. Wilkerson GB, Colston MA, Short NI et al (2004) Neuromuscular changes in female collegiate athletes resulting from a plyometric jump-training program. J Athl Train 39(1):17–23

Sports-Specific Programs for Soccer, Basketball, Volleyball, and Tennis

15

Sue D. Barber-Westin and Frank R. Noyes

Contents

S.D. Barber-Westin, B.S. (✉)
Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA
e-mail: sbwestin@csmref.org

F.R. Noyes, M.D.
Cincinnati Sportsmedicine and Orthopaedic Center, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

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 what they perceive as 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. 17 and 18. Therefore, the authors 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 [3]. The programs offer a unique blend of neuromuscular retraining and sport-specific enhancement tasks to both improve player skill and aerobic fitness and decrease the risk of a

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_15, © Springer-Verlag Berlin Heidelberg 2012

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 [22], Sportsmetrics Volleyball [20], Sportsmetrics Soccer [21], and Sportsmetrics Tennis [4] programs.

All sports-specific neuromuscular and performance programs begin with a 5- to 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. 14. The programs then move to sport-specific agility, speed, and aerobic conditioning which are described below. Strength and static flexibility exercises are then performed as described in Chap. 14.

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 decelera-

Fig. 15.1 (**a**) Valgus knee position on a sidecut, (**b**) loss of hip and knee flexion angles during deceleration just prior to a sidecut, (**c**) knee hyperextension and foot far in front of center of body mass upon planting for a sidecut

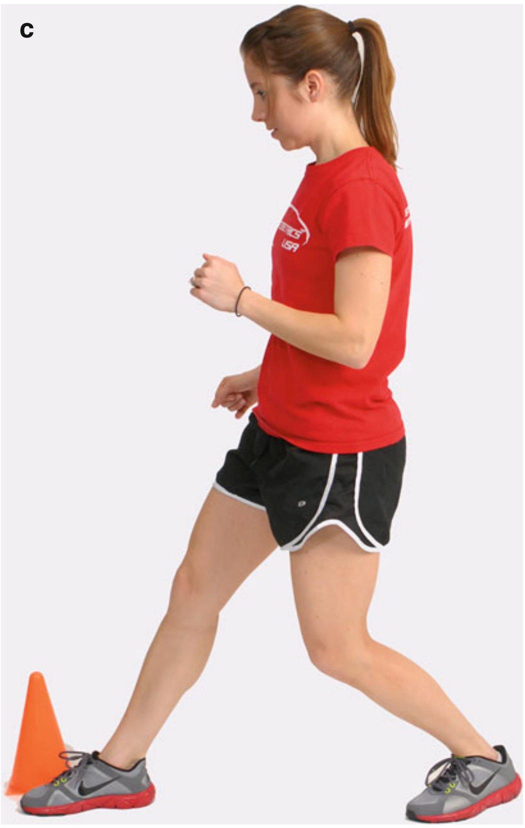


Fig. 15.1 (continued)

tion where the knee is near full extension and the foot is firmly fixed flat on the playing surface [2, 13]. 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 to males during various cutting maneuvers, such as an earlier onset of vastus lateralis activity and a longer duration of rectus femoris activity [6, 10, 12, 14, 15, 25]. Women have demonstrated during unanticipated cutting maneuvers greater knee abduction, hip external rotation, and ankle pronation [5, 6, 14]. During sidecutting, women have reduced knee and hip flexion angles and increased peak knee valgus and ankle pronation angles compared to men [17, 18] These findings may partially explain the gender disparity in ACL noncontact injuries that occur during cutting and pivoting [6].

ACL injury prevention training programs should include instruction to avoid these at-risk situations during landing from a jump, deceleration, cutting, and pivoting maneuvers [1, 8]. 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 training 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 [7, 24]. 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 [19, 23, 24]. 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 [7]. 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 [7].

Recommended instructions for agility and reaction drills include the following (Fig. 15.1) [2, 8, 11, 16, 26, 27]:

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 greater than 30°.
7. Avoid a valgus lower limb position.
8. Keep the knees over the ankles and do not allow them to extend over the toes.
9. During deceleration, use three short steps to reduce speed instead of one step.
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 [9].
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 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.

Soccer (Table 15.1)

Agility and Reaction Drills

Serpentine Run

Arrange six cones in a zigzag pattern within a 15 × 37 ft (4.6 × 11.3 m) area (Fig. 15.2). The athlete begins on the left of the first cone and sprints across to the next cone in the pattern. Upon reaching the second cone, the athlete decelerates and goes around the cone without stopping. The athlete reaches down and taps the top of the cone, then immediately accelerates to the next cone and repeats the decelerate/tap/accelerate sequence. Once the last cone is reached, an instructor presses the athlete and forces them to cut either right or left. The athlete then jogs back to the starting position.

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. 15.3). The athlete stands in the middle facing the 12 o'clock cone, which is the neutral position. The instructor calls out 1 of the 4 positions, and 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.

Modified Shuttle Run

Arrange seven cones in a zigzag pattern within a 10 × 30 ft (3.0 × 9.1 m) area (Fig. 15.4). 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

Table 15.1 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 ft (9.1 × 9.1 m) box, 2 reps
	7–9	Sprint-quick feet-listen	45 s, 2 reps
	10–12	Nebraska drill	30 ft (9.1 m) long, 4 reps
	10–12	Reaction drill-watch instructor point	45 s, 2 reps
	13–15	Illinois drill	15 × 10 ft (4.6 × 3.0 m), 4 reps
	13–15	Reaction mirror drill, pressing	60 s, 2 reps
	16–18	T-drill: 5-10-5	4 reps
	16–18	Advanced wheel drill: listen to instructor	60 s, 2 reps
Acceleration, speed, endurance	1–3	Partner push-offs, hold 5 s	5 reps
	1–3	Sprint-backpedal	½ field or 50 yd (45.7 m), 5 reps
	1–3	Jog	4 laps around field (1,280 yd, 1,170 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
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

(continued)

Table 15.1 (continued)

Component	Session no.	Exercise	Duration
Strength training	1–18	Resistance band: squats Resistance band: lunges Single-leg heel raise 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	30 s all exercises: sessions 1–6 45 s all exercises: sessions 7–12 60 s all exercises: sessions 13–18

[a]The dynamic warm-up, jump training, and static flexibility exercises are described in Chap. 14

during the cutting maneuvers as shown in Fig. 15.4. Once the last cone is reached, the athlete sprints to midfield, then jogs back to the starting position.

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."

Square Drill

The athlete begins at the back corner of a 30 × 30 ft square (9.1 × 9.1 m, Fig. 15.5). 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.

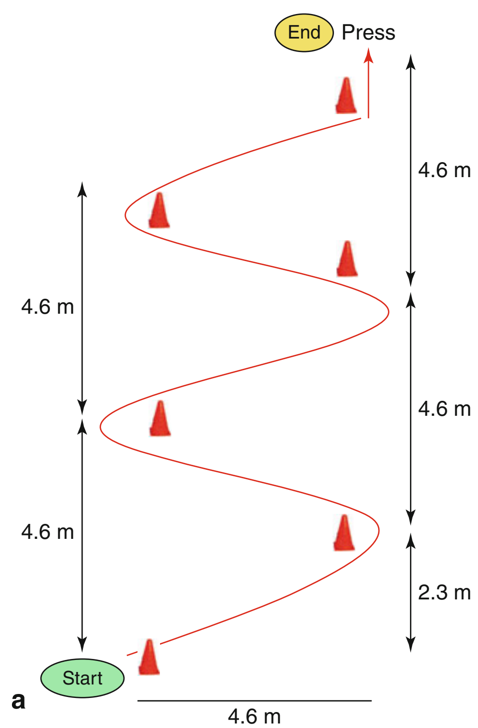
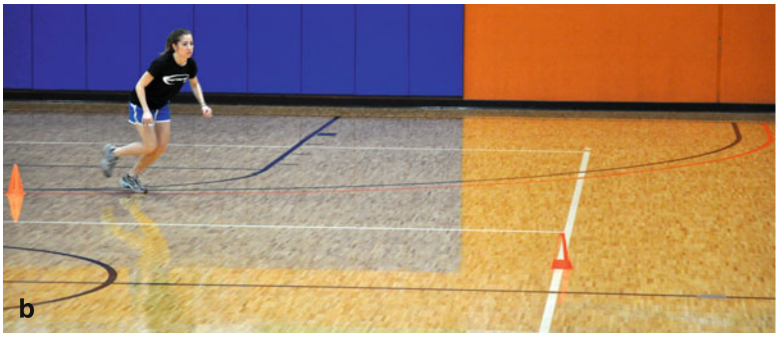
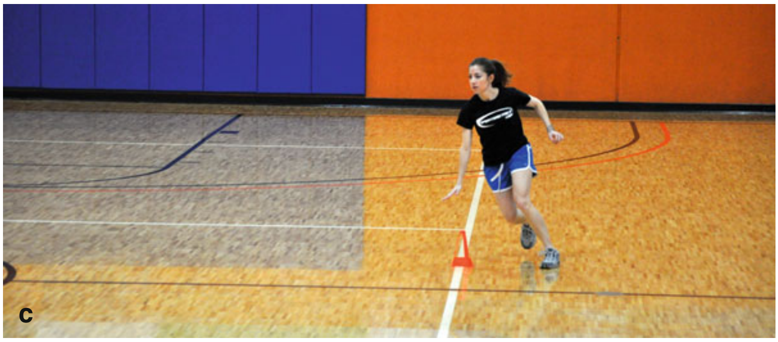


Fig. 15.2 Serpentine run (**a**–**c**)

Fig. 15.2 (continued)





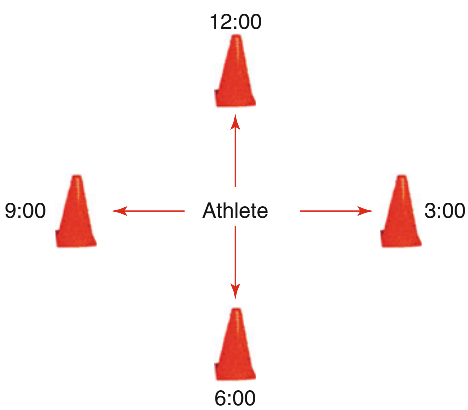


Fig. 15.3 Wheel drill

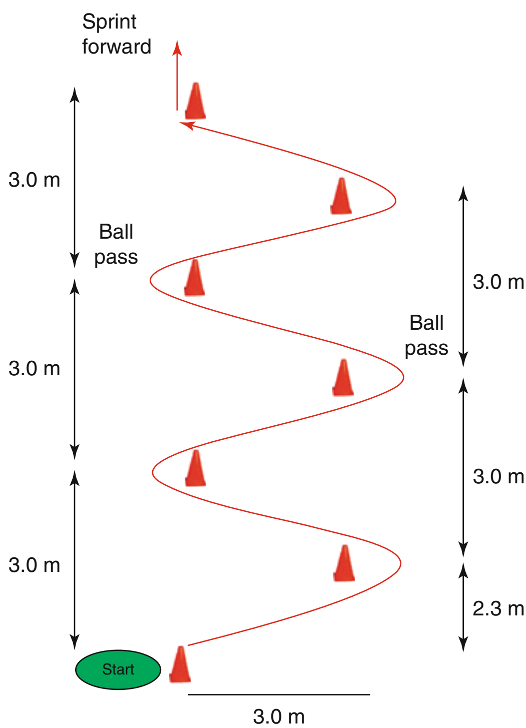
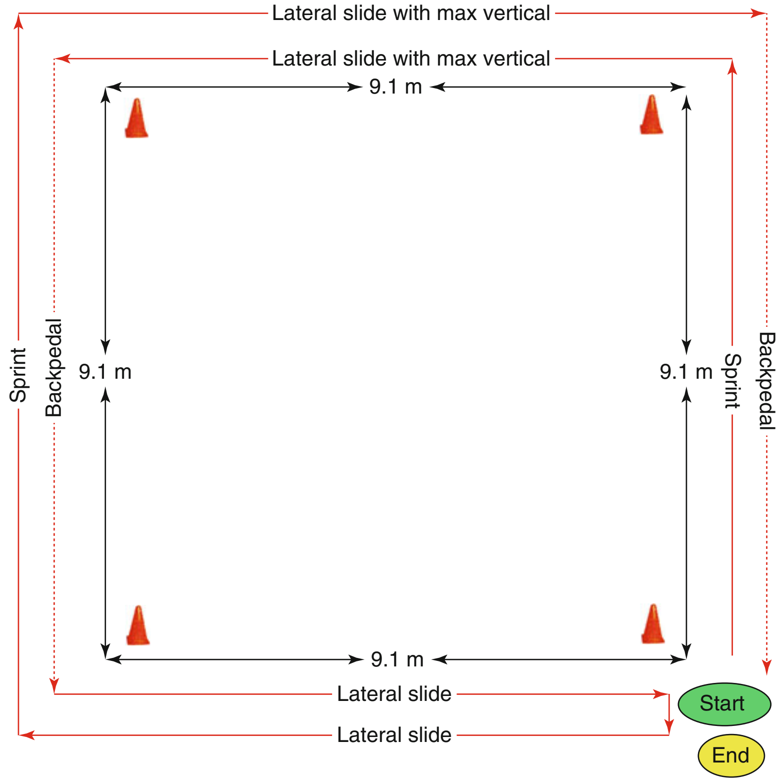


Fig. 15.4 Modified shuttle run

Fig. 15.5 Square drill



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."

Nebraska Agility Drill

Arrange two cones 30 ft (9.1 m) apart (Fig. 15.6). 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.

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.

Illinois Drill

Arrange four cones in a 30 × 30 ft (9.1 × 9.1 m) square (Fig. 15.7). Place four cones in a line in the center of the square, approximately 3–4 ft (0.9–1.2 m) apart. Beginning at the bottom left cone, the athlete sprints forward to the top left cone. While reaching down to tap the top of the cone, a tight cut is done around the cone. The athlete sprints to the first middle cone and then zigzags, cutting around each of the four cones

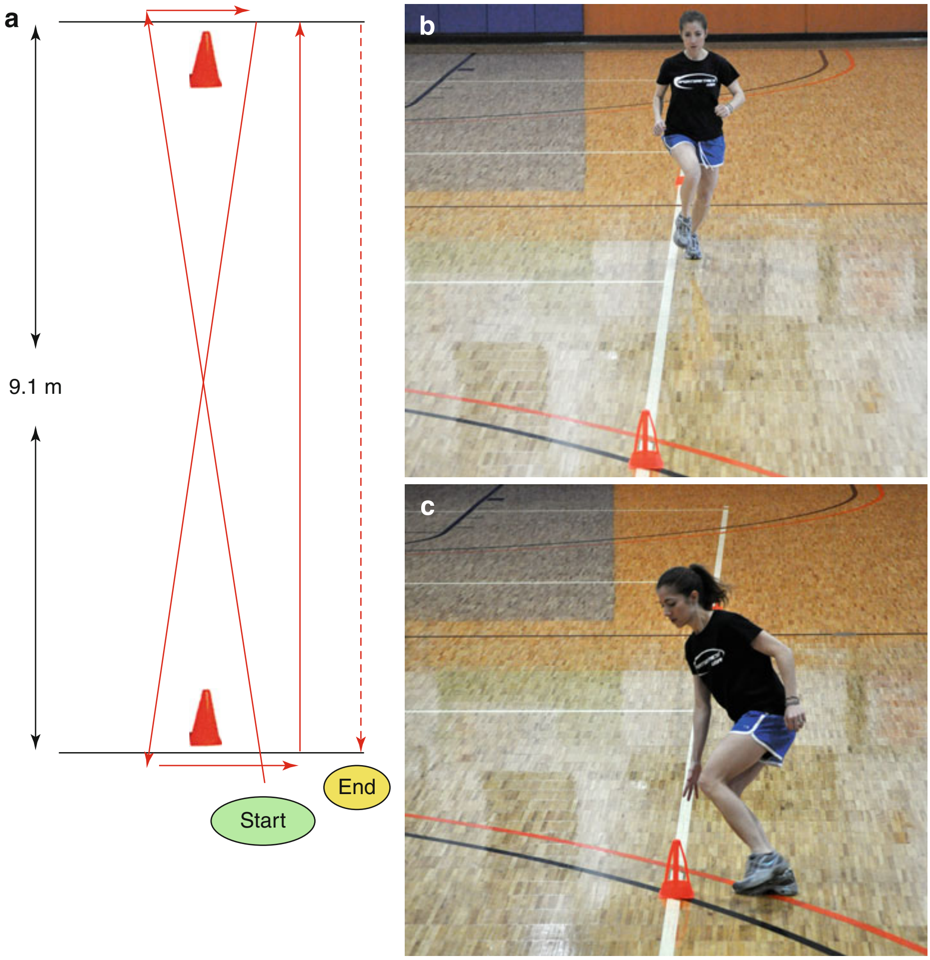


Fig. 15.6 Nebraska agility drill (**a**–**c**). *Solid lines* indicate forward sprinting; *dotted line* indicates backpedaling

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.

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.

T-Drill: 5-10-5

Arrange three cones and a start/finish marker so that they form the capital letter "T" (Fig. 15.8). 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

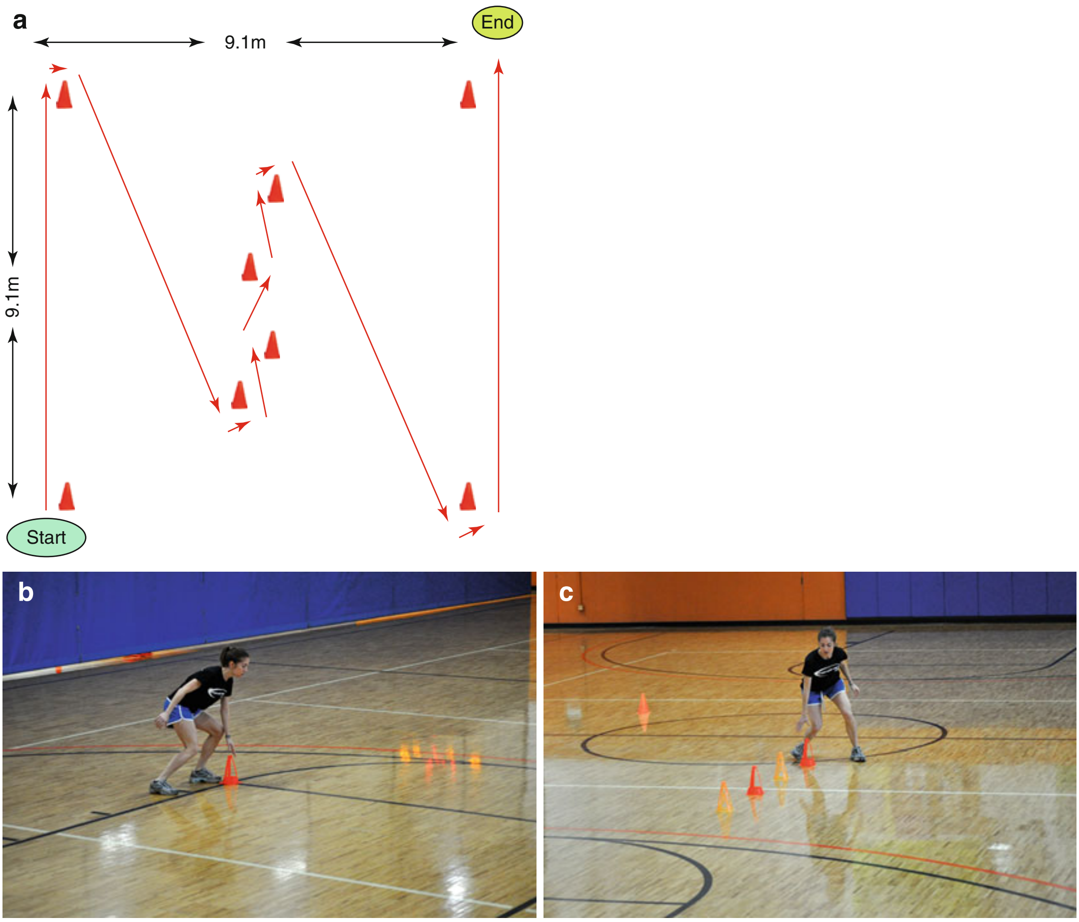


Fig. 15.7 Illinois drill (**a**–**c**)

cone, sprints to the far right cone, taps that cone, sprints to the center cone, taps that cone, and backpedals to the starting position.

Advanced Wheel Drill: Listen to Instructor

Arrange 8 cones, each approximately 7 ft (2.1 m) from center. Place 2 cones at the 12 o'clock position, 2 at the 3 o'clock position, 2 at the 6 o'clock position, and 2 at the 9 o'clock position. The athlete begins facing the 12 o'clock cones, with "quick feet" constantly and quickly moving under the body. The instructor calls 1 of the 4 positions and athlete responds by immediately running between the 2 cones and holding the quick feet position until instructor calls "back." The athlete returns to the center, keeping feet moving.

Acceleration, Speed, and Endurance Drills

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. 15.9). The sprinter assumes a starting position and leans forward against the resister. On command, the sprinter begins sprinting against the resister, driving their knees upward and forward, attempting to move forward. The resister places enough resistance against the sprinter to keep them stationary or moving only slowly forward. The sprinter counts out loud for 5, 10, or 15 s. When the sprinter has finished counting, the resister

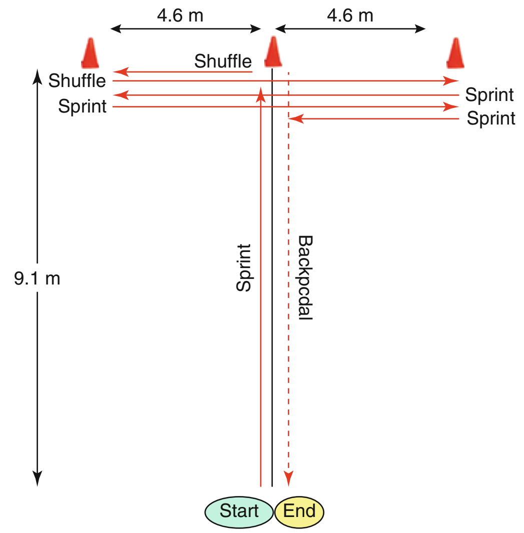


Fig. 15.8 T-drill. The shuffles and sprints at the top of the "T" are done in a straight line. The figure depicts the five segments individually for illustrative purposes only

Fig. 15.9 Partner push-offs

rolls off to the side and allows the sprinter to accelerate forward for five to ten strides. Then, the partners switch rolls and complete the drill again.

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.

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, then the athlete backpedals at ¾ speed to the starting position.

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.

Box Drill, Sprint-90°-Backpedal

The athlete begins at the bottom right corner of the penalty box (Fig. 15.10). Upon command, they sprint forward to the top of the box and perform a 90° turn by pivoting on the left foot and turning over the right shoulder. The athlete should be facing the right-hand sideline. They backpedal the length of the top of the box and, at the corner, make a 90° turn by pivoting on the right foot and turning over the right shoulder. The athlete should be facing the end line. They then sprint to the end line and make another 90° turn, pivoting on the left foot and turning over

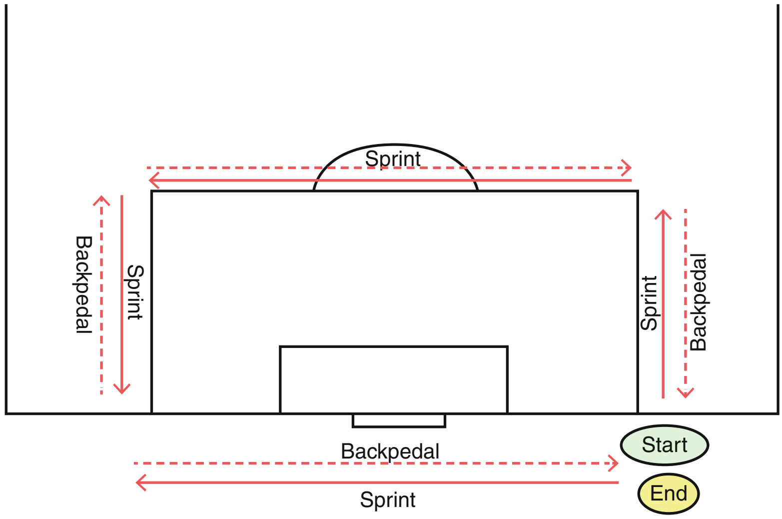


Fig. 15.10 Box drill, sprint-90°-backpedal

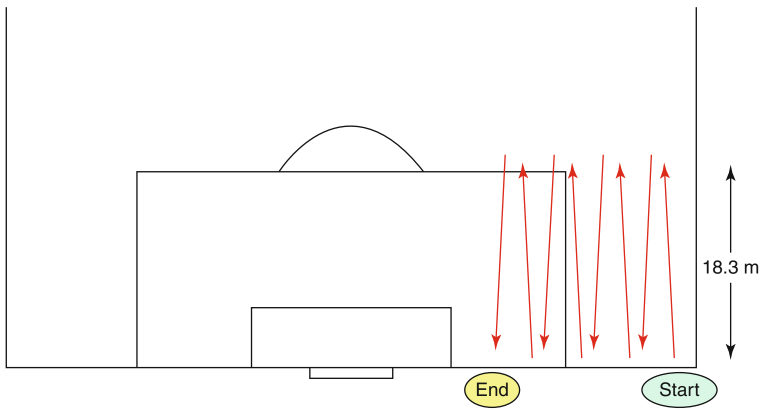


Fig. 15.11 Jingle jangle drill

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.

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.

Jingle Jangle

The athlete sprints a series of five repetitions of 20 yd (18.3 m), up and back (Fig. 15.11).

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.

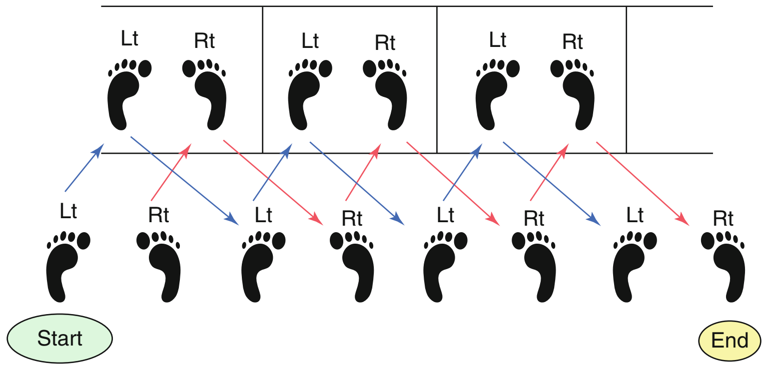


Fig. 15.12 Ladder: up-up and back-back. Only a portion of the 4.6 m ladder is shown for illustrative purposes

Ladders, Quick Feet, Additional Jump Drills

Ladder: Up-Up and Back-Back

A 15-ft (4.6 m) ladder is placed along the sideline (Fig. 15.12). 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.

Ladder: Toe Touches

The athlete begins in front of the ladder with the right toe touching one side of the ladder and left foot on the ground. On command, the athlete alternates toe touches from left toe to right toe. The feet are switched in the air as quickly as possible. Only the toes should touch the ladder. This exercise may be done with a soccer ball instead of a ladder.

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. 15.13). 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.

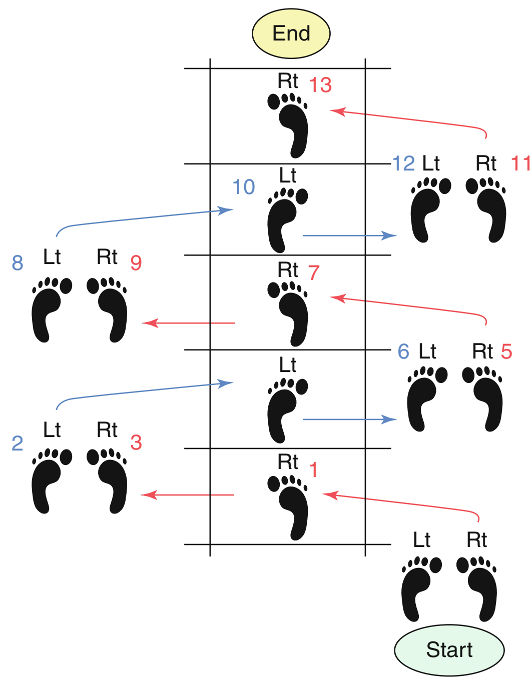


Fig. 15.13 Ladder: outside foot in. Only a portion of the 4.6 m ladder is shown for illustrative purposes

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. 15.14. 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

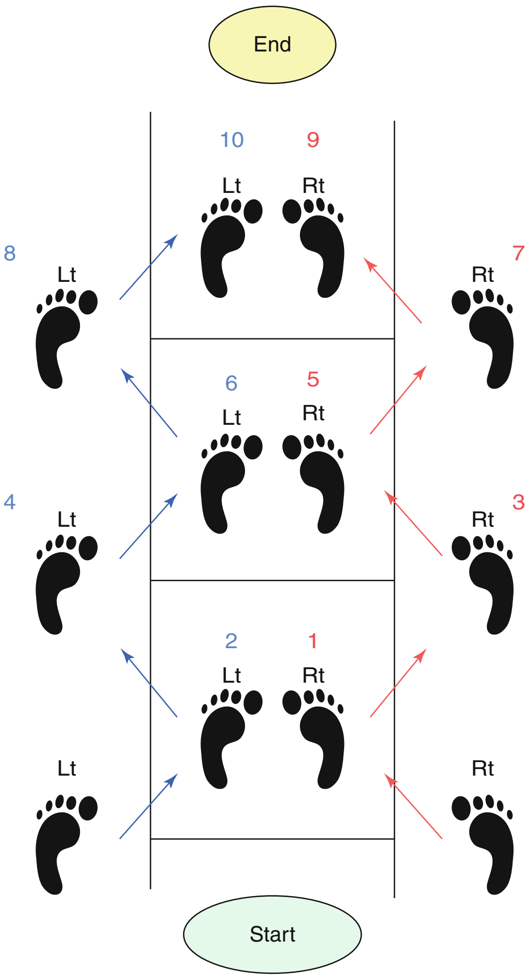


Fig. 15.14 Ladder: in-in, out-out. Only a portion of the 4.6 m ladder is shown for illustrative purposes

steps forward and laterally (to the outside right of the ladder) so that it is parallel to the ladder and in line with the ladder's rung. Once the right foot touches down outside of the ladder, the left foot steps forward and laterally (to the outside left of the ladder) so that it too is parallel to the ladder and in line with the rung. Once the left foot is down, the right foot steps forward and laterally into the next ladder "square," followed immediately by the left foot. The athlete continues this pattern along the length of the ladder. Upon reaching the end of the ladder, the athlete follows the same pattern described above but navigates the footwork backward in order to return to the starting position.

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. 15.15). 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.

Dot Drill: Double-Leg Jumps

For all of the dot drills, the athlete should be reminded to keep 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. 15.16. The athlete jumps to B, then continues to C, D, E, C, and back to A.

Dot Drill: Split-Leg Jumps

The athlete performs the double-leg jump pattern, ending with both feet on C shown in Fig. 15.17. 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, then jumps with split feet to D and E. The athlete then returns back the same way without turning around.

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. 15.18. The athlete jumps to C with both feet, 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.

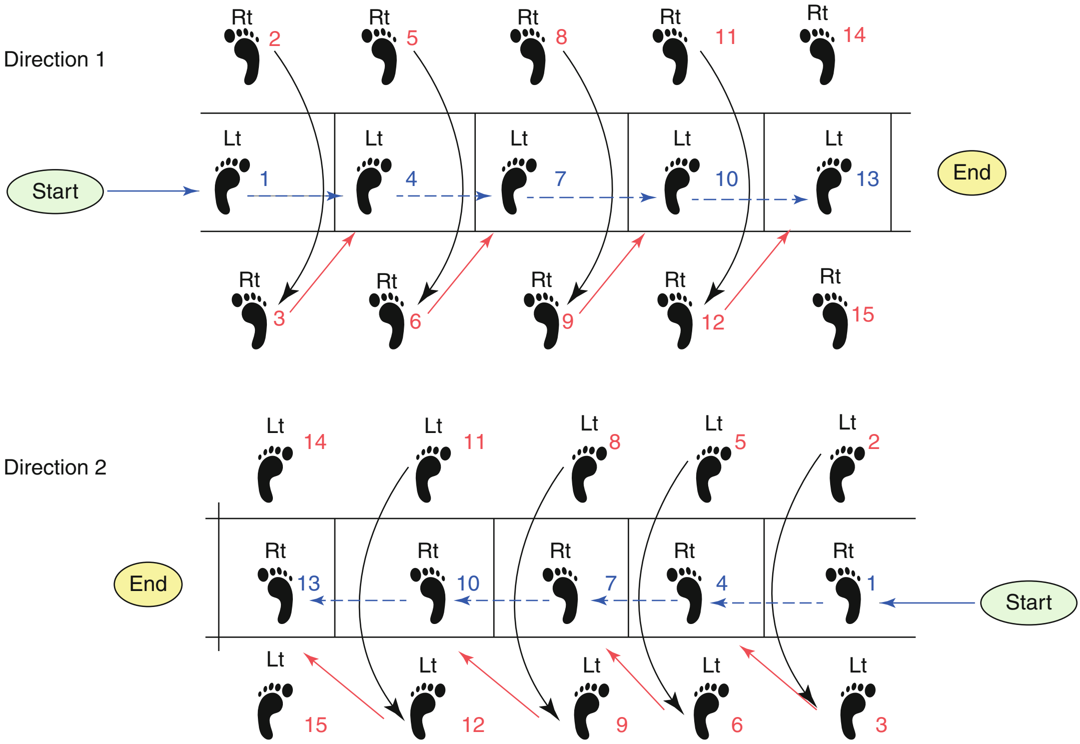


Fig. 15.15 Ladder: 1 foot forward, 1 foot backward. Only a portion of the 4.6 m ladder is shown for illustrative purposes

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. 15.19). 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, then jumps with the left foot only to B to C to D to E to C to A and to B.

Dot Drill: Combo All Jumps

Perform all four patterns as described above.

> **Critical Points**
> - Twelve agility and reaction drills (2 per session)
> - Eight acceleration, aerobic speed, and endurance drills (3 per session)
> - Ten ladders, quick feet, and additional jump drills (2 per session)

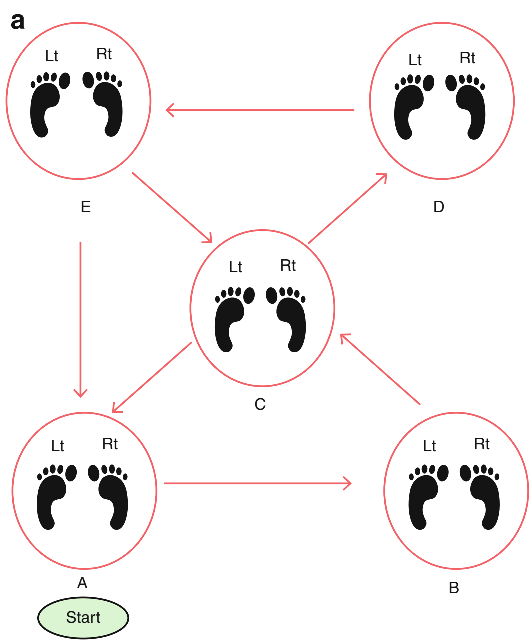


Fig. 15.16 Dot drills: double-leg jumps (**a**-**d**)

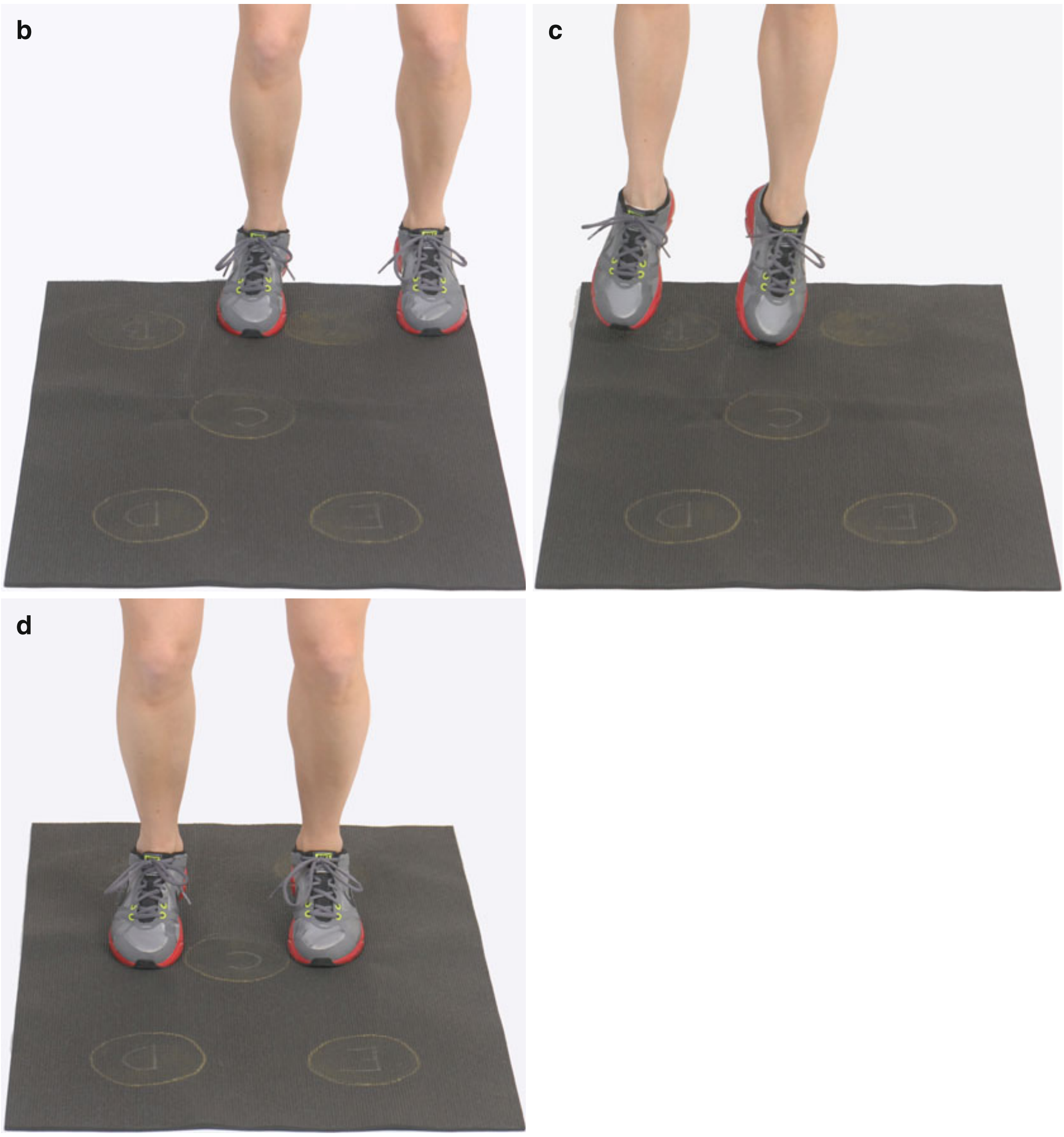


Fig. 15.16 (continued)

Basketball (Table 15.2)

Agility and Reaction Drills

Shuttle Drill

A course is set with six cones in a zigzag pattern within a 15 × 30 ft (4.6 × 27.4 m) area as shown in Fig. 15.20. Beginning at the 1st cone, the athlete sprints diagonally toward the 2nd cone. Upon approaching the 2nd cone, the athlete decelerates to allow for a defensive closeout. As soon as the closeout is performed, the athlete immediately accelerates to the 3rd cone and performs a jump shot without a ball. Then, the athlete sprints to the 4th cone, decelerates, cuts around and touches the cone, and accelerates to the 5th cone. The athlete decelerates and performs a sharp cut around the 5th cone and sprints to the 6th cone where a 90° transition is done. The athlete then backpedals until the sideline is reached.

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. 15.21. 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.

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.

Figure 4 Drill

Four cones are arranged as shown in Fig. 15.22. 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.

Square Drill

The athlete begins at the back corner of a large square as shown in Fig. 15.5. Moving around the

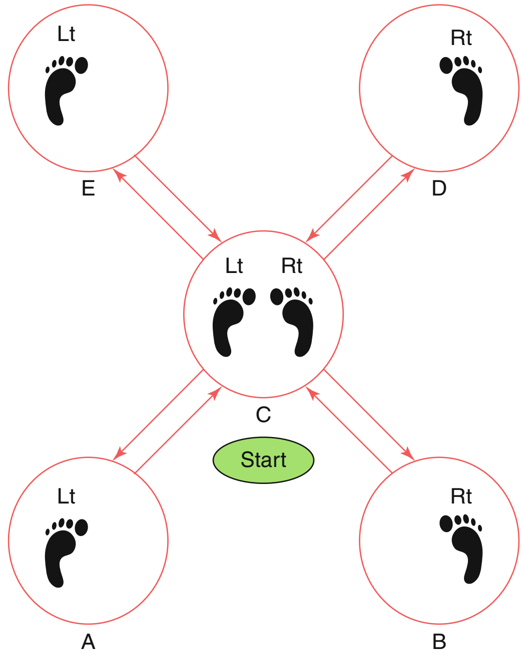


Fig. 15.17 Dot drills: split-leg jumps

a

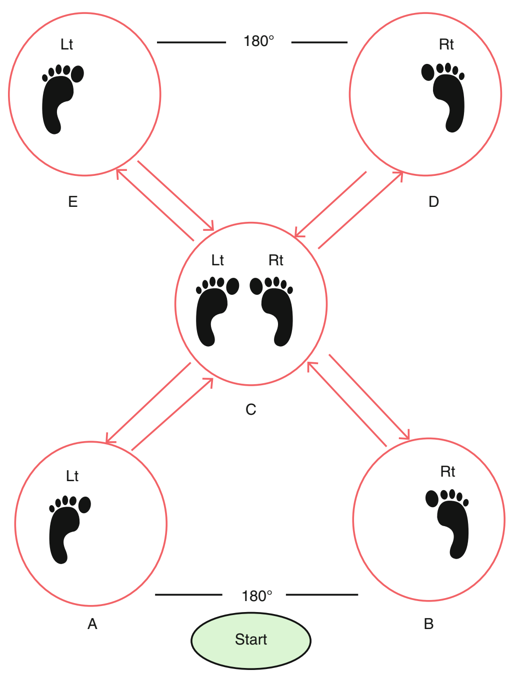


Fig. 15.18 Dot drills: 180° split-leg jumps (**a**–**d**)

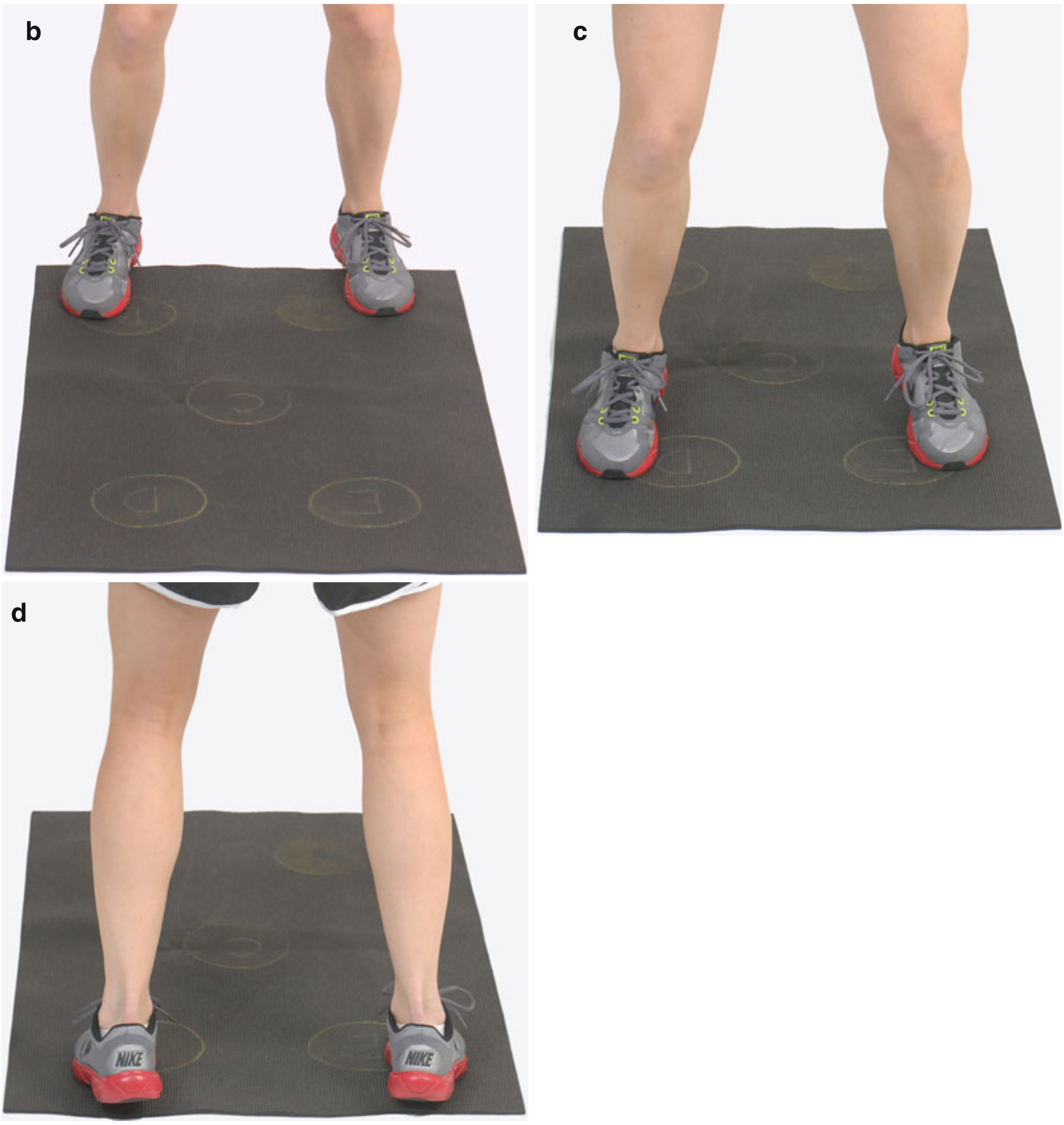


Fig. 15.18 (continued)

outside of the square, the athlete sprints forward, slides laterally across, jumps up to a maximal vertical between each slide, backpedals to the backside, and slides laterally across the back of the square to the starting position. Then, the direction is reversed and the pattern repeated, starting with the lateral slide. Once the technique for this drill has been mastered, a ball may be incorporated. As the athlete moves laterally, the ball is passed to the athlete for a quick shot or a pass back to the instructor.

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. 15.23. 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

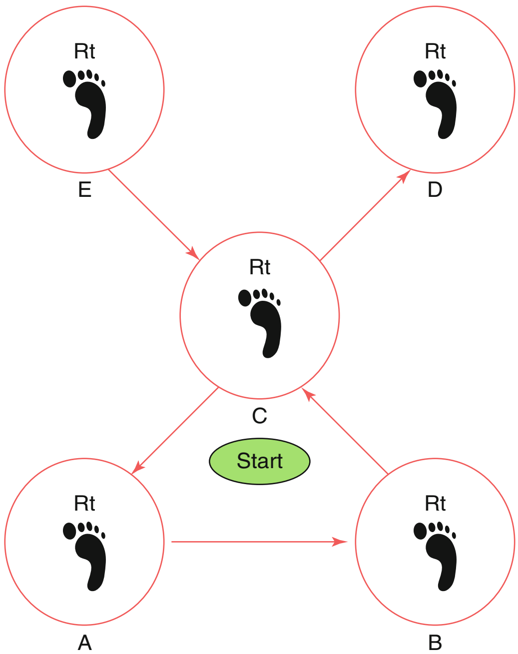


Fig. 15.19 Dot drills: single-leg hops

section "Ladder: In-In, Out-Out." At the end of the ladder, the athlete shuffles to the right until they reach the 3-point line. At this point, the instructor passes a ball to the athlete where they attempt to make an outside shot. This athlete then gets in line for "start B." At start B, the athlete shuffles to the left, sprints forward, shuffles to the right, sprints forward through the ladders, and shuffles forward toward the free throw line where an instructor passes the ball for a shot.

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.

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. 15.24). 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, 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, 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.

Irish D Drill

The athlete begins at the baseline, underneath the basket (Fig. 15.25), and performs five power jumps. The athlete then moves using defensive slides along the baseline to the 3-point line. They sprint from the 3-point line to the elbow and then perform defensive slides from the elbow to the middle of half-court. From half-court, the athlete sprints straight to the backboard. They perform five more power jumps under the backboard and then repeat the defensive slide/sprint pattern on the opposite side to complete 1 repetition.

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. 15.8. 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.

Kill the Grass Drill

Five to ten players, each with a ball, are positioned inside the lane. The objective is for each player to move around the confined space while dribbling a basketball. The athletes should use both hands to dribble, change direction, and continuously move around. A variation on this drill is to have the athletes play knockout where each player tries to make the others lose control of the

Table 15.2 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

(continued)

Table 15.2 (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	
		Supine hamstring bridge	Lower extremity done on Monday and Friday
		Abdominals of choice	Upper extremity done on Wednesday
		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. 14

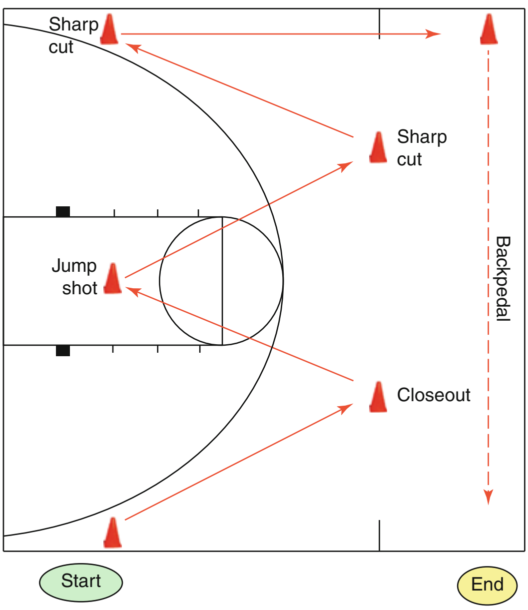


Fig. 15.20 Basketball shuttle drill. *Solid red lines* indicate forward sprints; *dotted line* indicates backpedaling

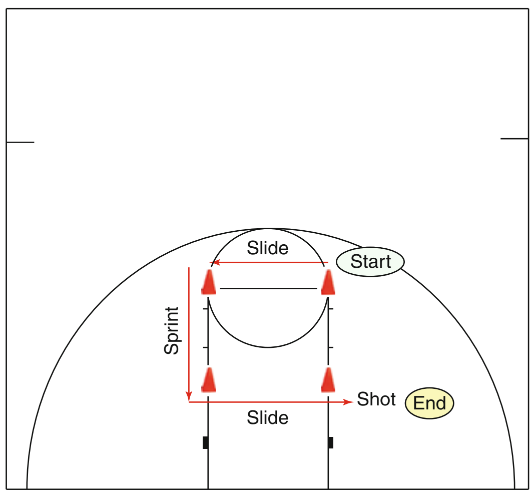


Fig. 15.21 Maze drill

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.

Acceleration, Speed, and Endurance Drills

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

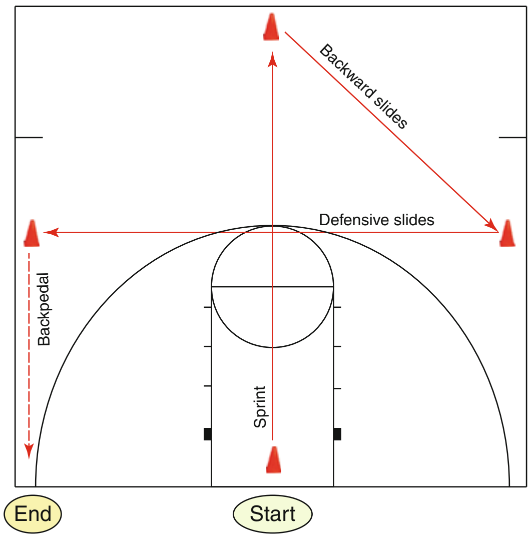


Fig. 15.22 Figure 4 drill

knee up into the chest (Fig. 15.26). 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.

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.

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. 15.27).

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.

¼ Eagle Sprints-Backpedal

See section "¼ Eagle Sprint-Backpedal."

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.

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.

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.

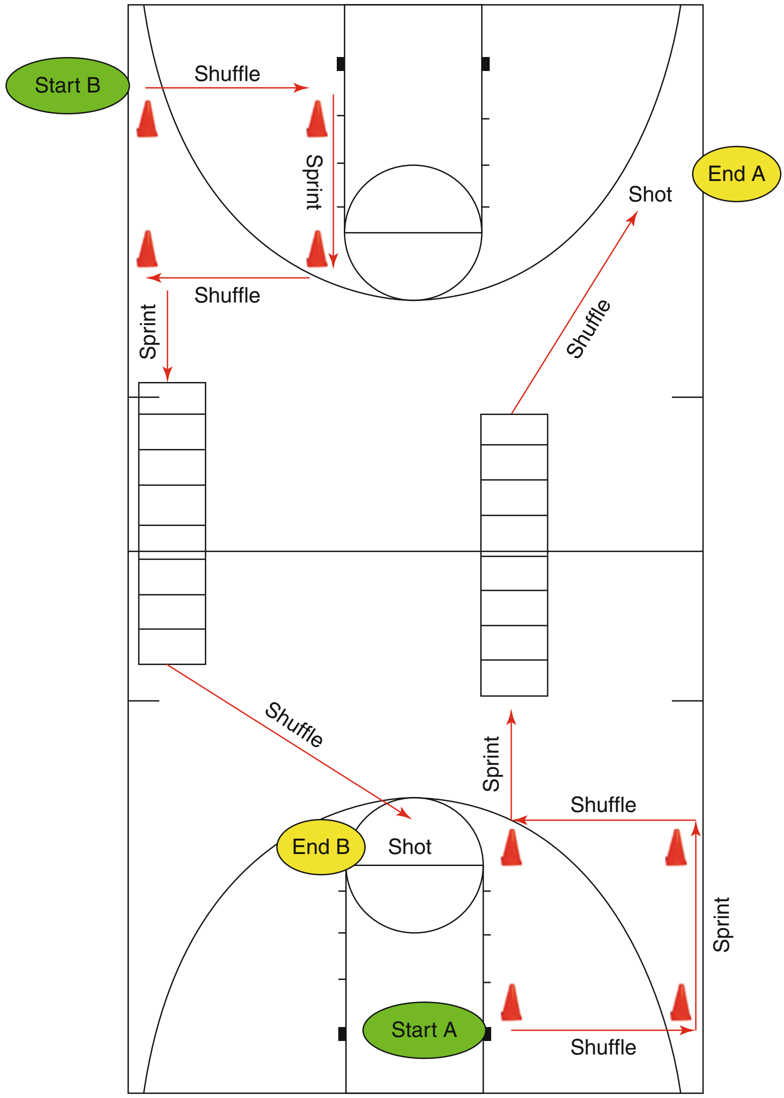
Sprint-180°-Backpedal

See section "Sprint-180°-Backpedal."

Sprint-Quick Feet-Backpedal

The players begin at the end line and sprint until the instructor commands "stop," at which time the athletes keep their feet moving quickly in the same spot until the instructor commands "go," and they then backpedal back to the end line again. Pattern is continued for amount of time desired.

Fig. 15.23 4 dot drill, ladder



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.

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. 15.28). 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 signal for the next teammate to begin; the winner is the first team to have all of their members cross the opposite baseline.

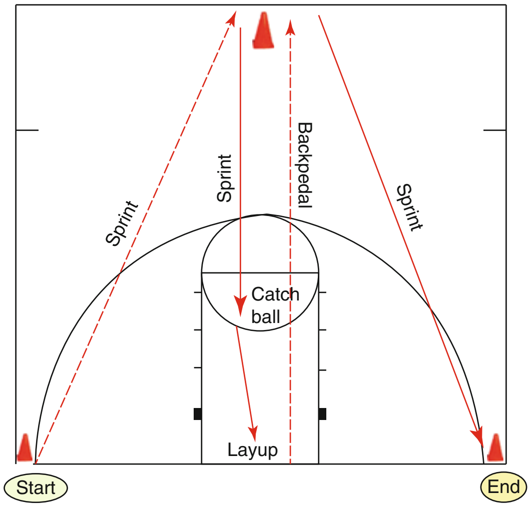


Fig. 15.24 Shoot and sprint drill

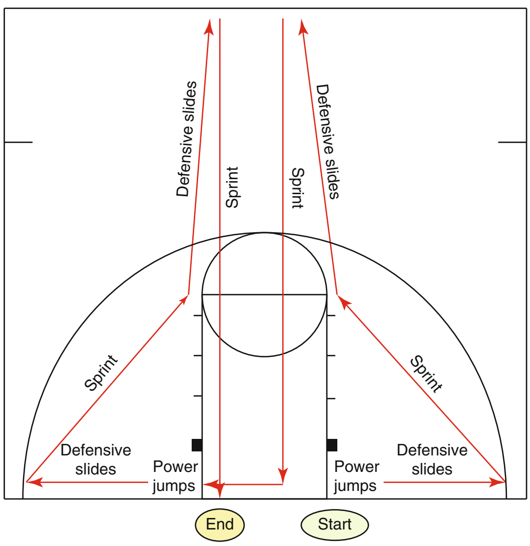


Fig. 15.25 Irish D drill

Ladders, Quick Feet, Additional Jump Drills

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. 15.29). 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.

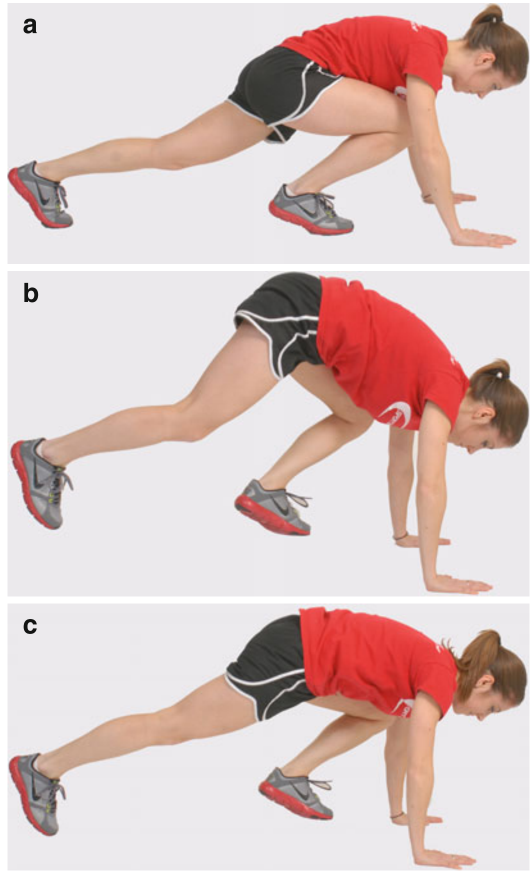


Fig. 15.26 Mountain climbers (**a**–**c**)

Ladder: Up-Up/Back-Back

See section "Ladder: Up-Up and Back-Back."

Ladder: Outside Foot In

See section "Ladder: Outside Foot In."

Ladder: In-In, Out-Out

See section "Ladder: In-In, Out-Out."

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. 15.30). The athlete jumps up in the air, both feet leaving the ground at the same time, and scissor the legs

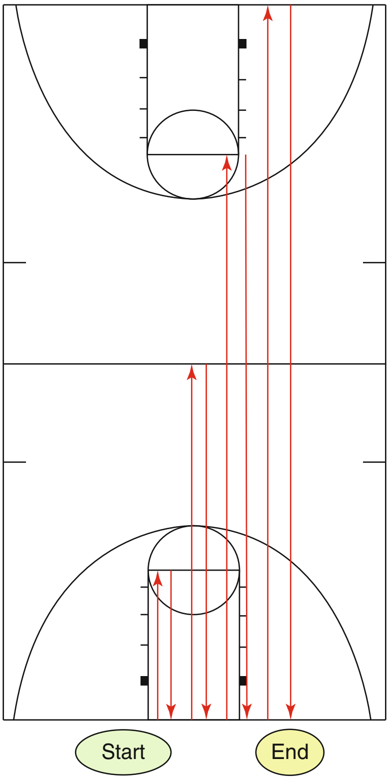


Fig. 15.27 Suicides on a basketball court. Run is done in a straight line; the figure depicts the eight segments individually for illustrative purposes only

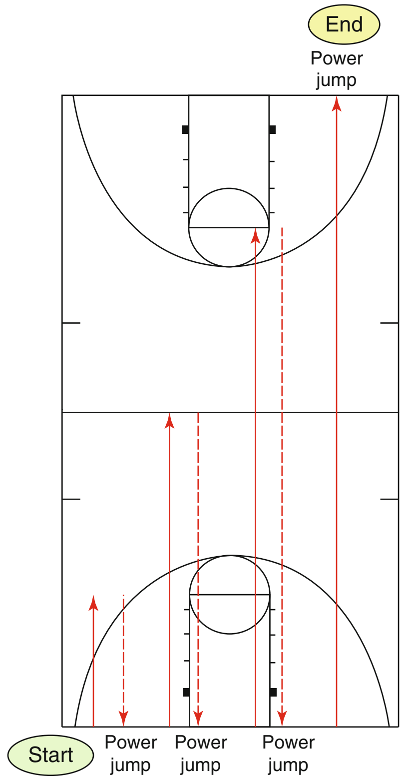


Fig. 15.28 Power rebounds relay. *Solid lines* indicate forward sprints, *dotted lines* indicate backpedaling

so 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 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.

Ladder: Icky Shuffle

The athlete begins by stepping the right foot in the first box, followed by the left foot (Fig. 15.31). 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.

High Knee Ball Toss Over Barrier

A barrier and partner are required for this drill. The athlete is positioned to the right of the barrier on the right leg, with the left knee drawn toward chest in a "Heisman" position (Fig. 15.32). The athlete jumps over the barrier off of the right foot and lands on the other side of the barrier on the left foot, with the right leg now drawn up toward chest in the "Heisman" position. Immediately upon landing, the partner gives a chest pass, and the athlete must catch and pass the ball back before returning to the other side of the barrier. As soon as the athlete lands back on the right side on the right leg, the partner passes the ball again, and the athlete passes it back. This pattern is continued back and forth over the barrier for 45 s.

Double High Knee Ball Toss Over Barrier

This is the same drill as described above, except a second barrier is added. Between the "Heisman"

Fig. 15.29 Ladder: high knees (**a**–**b**)

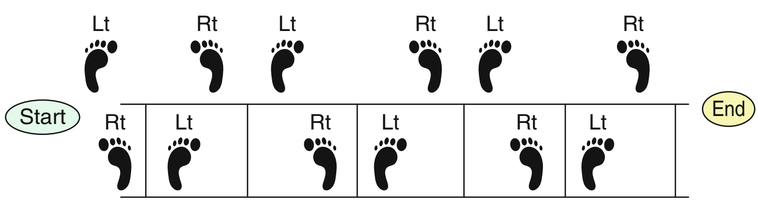


Fig. 15.30 Ladder: scissors. Only a portion of the ladder is shown for illustrative purposes

poses and partner chest passes, the athlete performs high knees over both barriers.

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.

Single-Leg Squat Jumps

The single-leg squat jump is similar to the squat jump described in Chap. 14, except the athlete begins on one leg and squats as low to the ground as possible without allowing the knee to come

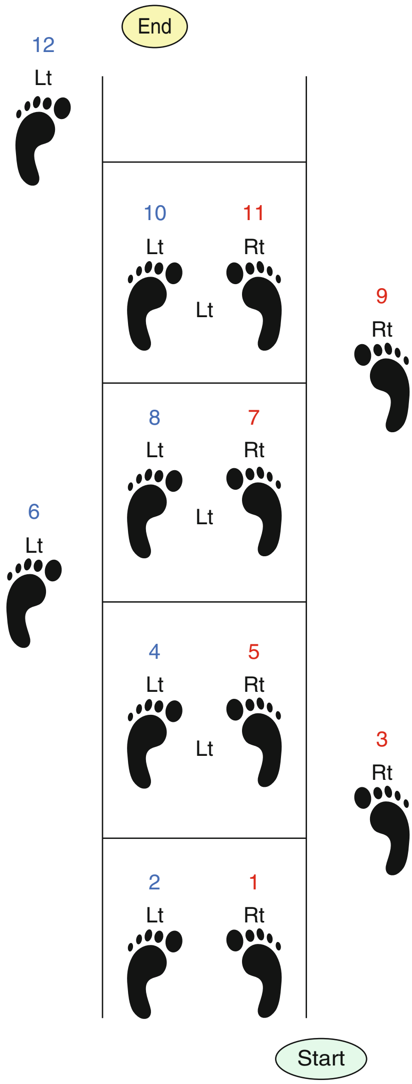


Fig. 15.31 Ladder: icky shuffle. Only a portion of the ladder is shown for illustrative purposes

forward over the toe or bending at the waist. Once 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.

180° Scissor Jumps

The 180° scissor jump is similar to the 180° jump described in Chap. 14. The athlete begins in a deep lunge position with right foot forward. They jump straight up, turn 180° over the left shoulder, and land in a deep lunge position facing the opposite direction. Now the left foot should be forward. The jump is repeated, turning over the right shoulder.

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."

Critical Points

- Eleven agility and reaction drills (2 per session)
- Twelve acceleration, speed, and endurance drills (3 per session)
- Twelve ladders, quick feet, and additional jump drills (3 per session)

Volleyball (Table 15.3)

Agility and Reaction Drills

Volleyball Shuttle Drill

Arrange six cones in a zigzag pattern within a 15 × 30 ft (4.6 × 9.1 m) area (Fig. 15.33). The athlete begins at the 1st cone and sprints diagonally to the 2nd cone. Upon approaching the 2nd 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 5th cone, the athlete accelerates to the 6th cone where they make a 90° transition and backpedal until the sideline is reached.

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 1 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. This pattern is continually repeated as the athletes

Fig. 15.32 High knee ball toss over barrier, "Heisman" position

Table 15.3 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

(continued)

Table 15.3 (continued)

Component	Session no.	Exercise	Duration
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 × 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
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. 14

rotate through each line, trying to keep the ball in the air.

Square Drill

See section "Square Drill."

Nebraska Drill

See section "Nebraska Agility Drill."

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, then the athletes switch positions and repeat the drill.

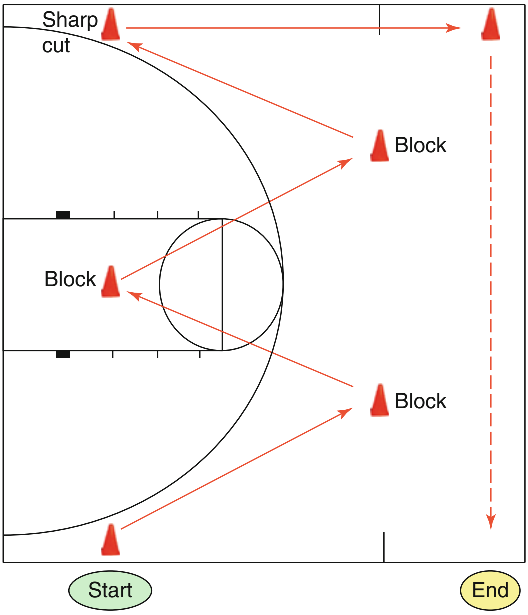


Fig. 15.33 Volleyball shuttle drill. *Solid red lines* indicate forward sprints; *dotted line* indicates backpedaling

T-Drill: 5-10-5

See section "T-Drill: 5-10-5."

Shuffle Set with Partner

This is the same drill as described for shuffle pass with partner, except the athlete receiving the ball jumps up to set the ball back to their partner.

Acceleration, Speed, and Endurance Drills

Partner Push-Offs

See section "Partner Push-Offs."

Sprint-Backpedal

See section "Sprint-Backpedal."

Acceleration with Band

See section "Acceleration with Band."

Mountain Climbers

See section "Mountain Climbers."

¼ Eagle into Sprint-Backpedal

See section "¼ Eagle Sprint-Backpedal."

Sprints with Ground Touches

See section "Sprint with Ground Touches."

Sprint-180°-Backpedal

See section "Sprint-180°-Backpedal."

Sprint-360°-Backpedal

See section " Sprint-360°-Backpedal."

Ladders, Quick Feet, Additional Jump Drills

Ladder: High Knees

See section "Ladder: High Knees."

Ladder: Up-Up/Back-Back

See section "Ladder: Up-Up and Back-Back."

Ladder: Outside Foot In

See section "Ladder: Outside Foot In."

Ladder: In-In/Out-Out

See section "Ladder: In-In, Out-Out."

Ladder: Scissors

See section "Ladder: Scissors."

Ladder: Icky Shuffle

See section "Ladder: Icky Shuffle."

Wheel Drill: Listen to Instructor

See section "Wheel Drill: Listen to Instructor."

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. 15.34). Immediately repeat the drill for one set.

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.

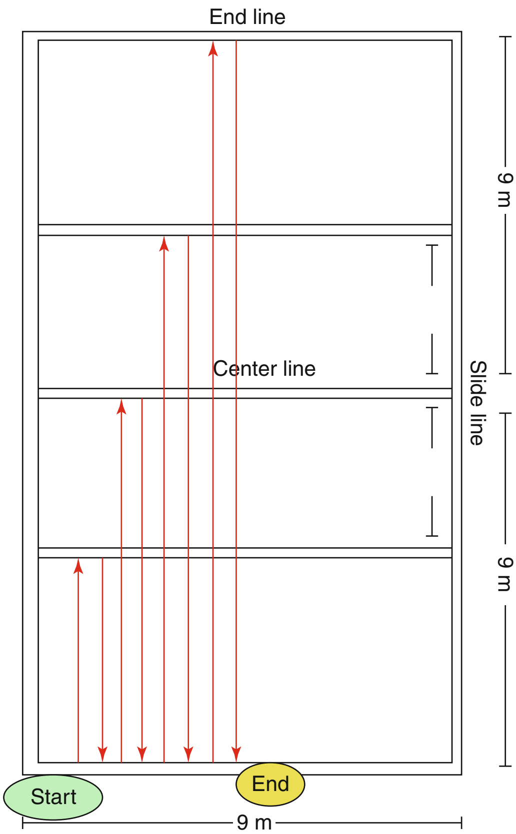


Fig. 15.34 Suicides on a volleyball court. Run is done in a straight line; the figure depicts the eight segments individually for illustrative purposes only

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.

Sprint-Stop Feet-Listen to Instructor

See section "Sprint-Stop Feet-Listen to Instructor."

Sprint-Quick Feet-Listen to Instructor

See section "Sprint-Quick Feet-Listen to Instructor."

Reaction Drill-Watch Instructor Point

See section "Reaction Drill-Watch Instructor Point."

Jingle Jangle

See section "Jingle Jangle."

Reaction Mirror Drill, Partner Pressing

See section "Reaction Mirror Drill, Partner Pressing."

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.

Power Rebounds Relay

See section "Power Rebounds Relay."

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."

Critical Points

- Eight agility and reaction drills (1–2 per session)
- Eight acceleration, speed, and endurance (2 per session)
- Eighteen ladders, quick feet, and additional jump drills (1–4 per session)

Tennis (Table 15.4)

Agility and Reaction Drills

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 holding the left shoulder. The athlete runs to the singles sideline of their forehand and swings the

Table 15.4 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 and 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)	90 s each side
Acceleration, speed, endurance	1–3	Suicides, 1 court	2 reps
	4–6	Net zigzag	2 reps
	4–6	Partner push-offs	5 s, 5 reps
	7–9	Forehand and backhand wide continuous hitting	8-6-6-8 reps
	7–9	Net zigzag	3 reps
	7–9	Partner push-offs	10 s, 3 reps
	10–12	Baseline random feed: forehand, backhand	1 min, 2 min
	10–12	Net zigzag	3 reps
	10–12	Sprint-quick feet-listen to instructor	60 s, 2 reps
	13–15	Suicides, 1 court	2 reps
	13–15	Suicides, 2 courts	1 rep
	13–15	Sprint-quick feet-listen to instructor	60 s, 3 reps
	16–18	Forehand and backhand wide continuous hitting	6-4-4-6 reps
	16–18	Suicides, 1 court	4 reps
	16–18	Suicides, 2 courts	1 rep
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	Up-up, back-back, sprint to cone, backpedal	2 reps
	10–12	Patterns 5 and 6	25 s each
	13–15	Up-up, back-back, sprint to cone, backpedal	3 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	2 sets × 8 reps
	1–6	Medicine ball backhand	2 sets × 8 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 × 10 shots each side
	7–9	ETCH-swing forehand, backhand, serve	2 sets × 15 shots each side
	16–18	Medicine ball twisting lunges	2 sets × 16 reps
	1–18	Backward lunge, add hand weight session 4	1 full court × 2–4 reps
	1–18	Single-leg toe raise, add hand weight session 4	3 sets × 10–20 reps each leg
	1–18	Seated press-ups	10–20 reps
	1–18	Regular or wall push-ups	3 sets × 10–20 reps
	1–18	Wall sits	3 sets × 45–60 s
	1–18	Wall sits, ball pressed between legs	3 sets × 45–60 s

(continued)

Table 15.4 (continued)

Component	Session no.	Exercise	Duration
	1–18	Abdominals, choose variety	150–300 reps
	1–18	Resistance band hip abduction, adduction	2–3 sets × 10–15 reps each side
	1–18	Tennis ball small circles	30–60 circles each arm
	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. 14

Fig. 15.35 Shadow swing baseline, forehand and backhand (**a**–**c**)

torso and shoulders in a complete forehand motion (Fig. 15.35) 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, 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 maintain their head up to focus on the ball and help with balance. Shoulder turns are exaggerated.

Alternating Short/Deep Balls, Forehand and Backhand

The instructor feeds the athlete alternating short and deep shots by tossing the ball from the

Fig. 15.36 Alternating short/deep balls forehand and backhand drill (**a**–**c**). *X* instructor, *P* player, *D* deep ball feed, *S* short ball feed

sideline (Fig. 15.36). 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, 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 sideways for short balls and hit with an open stance.

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 recovers back to the starting position. A total of 10 consecutive balls are fed to the forehand. After a 30-s rest, the same drill is repeated to the backhand.

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 8 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 maintain the head down, keep the upper body as stable as possible, make small adjustments with the feet, and stay low.

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.

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.

Rapid Return Serve Feeds Forehand and Backhand

This drill is similar to the rapid drop feed (section "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 8 balls to the forehand as rapidly as possible. After a 10-s rest period, the drill is repeated on the backhand side.

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. 15.37. The athlete proceeds through the ladder using the up-up, back-back pattern. Upon completion, the athlete sprints to

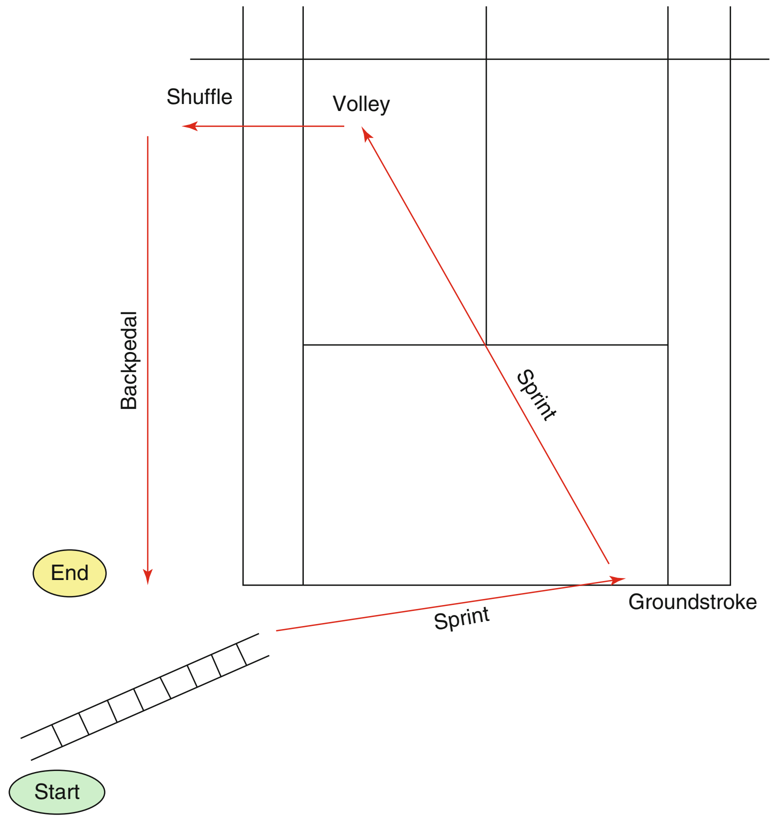


Fig. 15.37 Up-up, back-back, sprint to ground stroke, sprint to volley, forehand and backhand

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. 15.37, 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.

Acceleration, Speed, and Endurance Drills

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. On clay courts, the athlete should be encouraged to slide into the ball. On hard courts, small adjustment steps are emphasized.

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.

Net Zigzag

Five cones are placed in a zigzag pattern from the baseline to the net as shown in Fig. 15.38. 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 1st cone, and swings the racket to simulate a volley

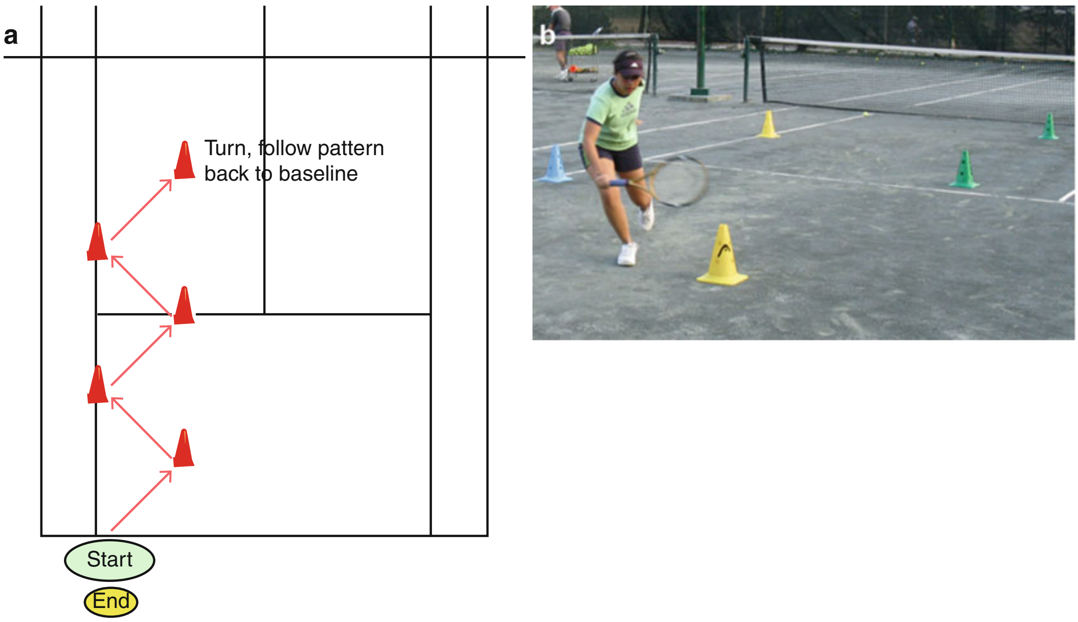


Fig. 15.38 Net zigzag drill (**a**–**b**)

directly over the cone. In the course depicted in Fig. 15.38, the 1st cone would indicate a forehand volley for a right-hand player. The athlete continues to the 2nd cone and swings the racket 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.

Partner Push-Offs

See section "Partner Push-Offs."

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 15.4. 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.

Baseline Random Feed Forehand and Backhand

The athlete begins in the middle of the baseline. The instructor randomly feeds balls to the forehand and backhand, within 4–6 ft (1.2–1.8 m) of the player, for 1 min without stopping. The athlete rests for 30 s, and then the instructor randomly feeds another round of ground strokes for 2 min without stopping. The athlete is reminded to focus on recovery footwork and to breathe continuously.

Sprint-Quick Feet-Listen to Instructor

See section "Sprint-Quick Feet-Listen to Instructor"

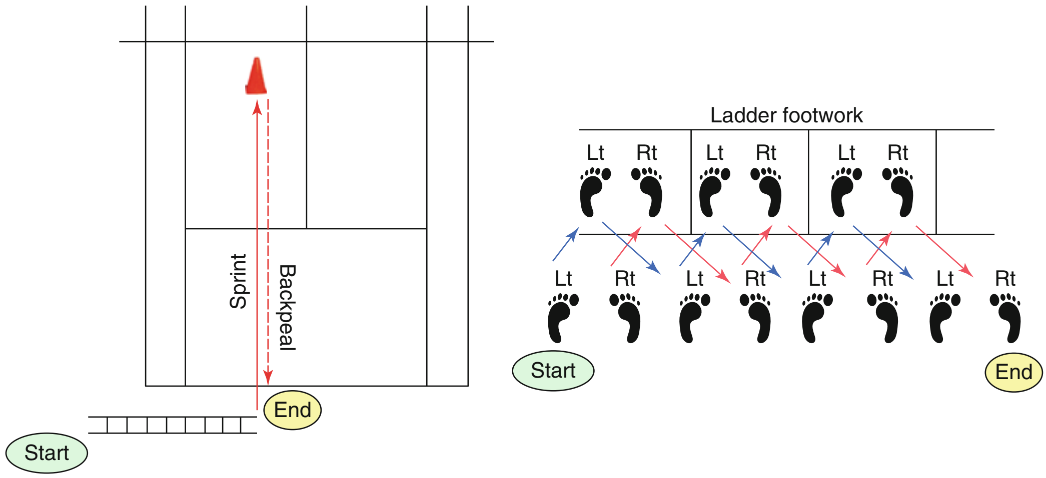


Fig. 15.39 Ladder: up-up, back-back, sprint to cone, backpedal

Ladders, Quick Feet, Additional Jump Drills

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. 15.39). A cone is placed 4 ft (1.2 m) from the net and in line with the end of the ladder. The athlete starts at the left end of the ladder, facing the net. The right foot is stepped 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 right foot is stepped 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. Then, the athlete sprints forward to the cone, touches the cone with their racket, and then runs backward in a controlled, balanced manner.

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.

Pattern Jumps

A series of ten jumps are performed in a 4-square pattern configuration with tasks of increasing difficulty (Fig. 15.40). Each square is approximately 2 × 2 ft (0.6 × 0.6 m). Two pattern jumps are performed each week (wk), beginning the 2nd 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.

On-the-Court Strength Training

In addition to the strength training exercises described in Chap. 14, other options were designed for Sportsmetrics Tennis that may be accomplished at the tennis facility. The equipment required are a medicine ball (2 lb [0.9 kg] minimum, heavier weighted balls for stronger players), handheld weights (two weights each, 2–10 lb [0.9–4.5 kg], in 1-lb [0.4 kg] increments), and large plastic balls or cushions for the wall-sitting exercises.

Medicine Ball Forehand, Backhand, and Overhead

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

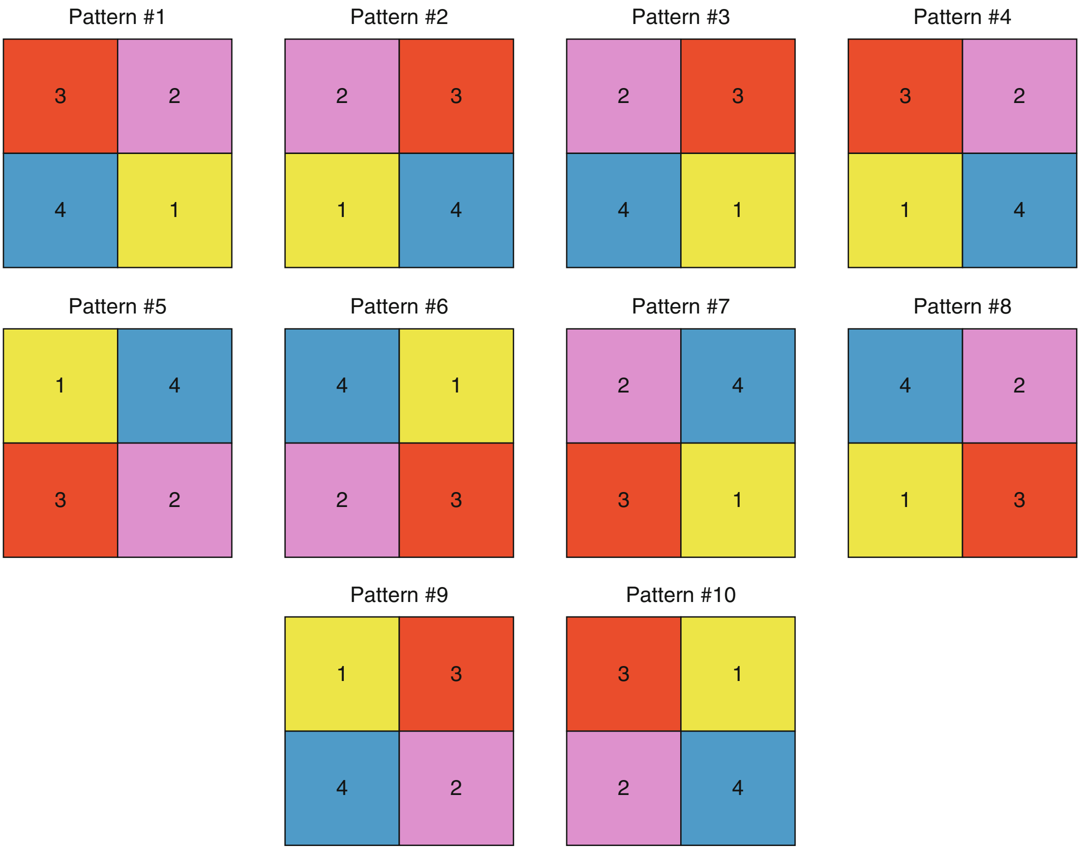


Fig. 15.40 Pattern jumps

Fig. 15.41 Medicine ball forehand and backhand (**a**–**b**)

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. 15.41). 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.

Backward Lunge

The athlete begins by stepping backward with 1 leg as far as possible. Keeping the back straight, the back leg is lowered toward the ground, stopping just before the knee touches the ground or as low as possible while maintaining balance and control. The front knee should stay directly over the ankle. The athlete lifts up and brings the front leg alongside the back leg, pauses, and then repeats this pattern for the duration shown in Table 15.4. 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. 15.42).

Fig. 15.42 Backward lunge with handheld weights

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.

Single-Leg Toe Raise

From a standing position, the athlete raises up on the toes of one foot, bringing the heel off of the ground. This position is held for 1–2 s and then slowly returned to the starting position. Initially, the athlete may need to hold onto the fence or other stable object for balance control. Athletes with very weak calf muscles may need to perform this exercise with both legs together initially. During training session #4, the athlete should add dumbbell weights (equal weight in both hands) during this exercise. To make the task ever more challenging, the athlete may

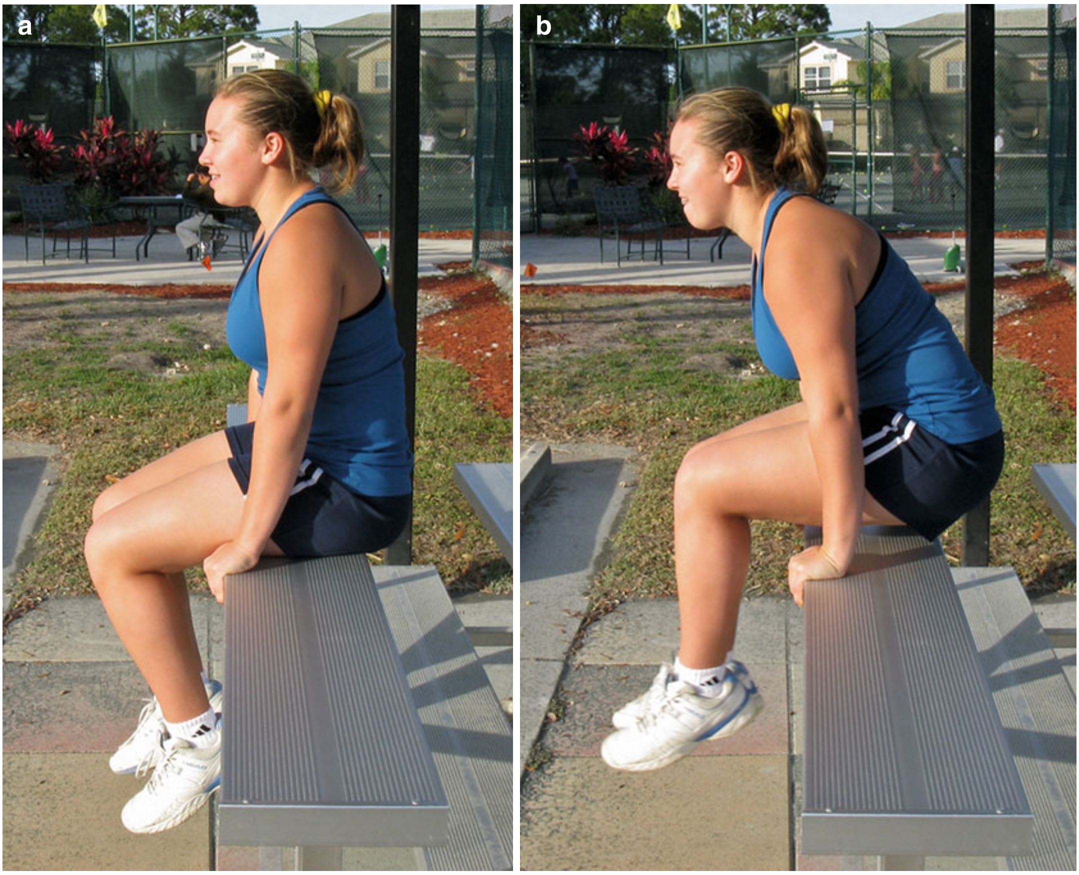


Fig. 15.43 Seated press-ups (**a**–**b**)

perform the exercise on a step or other elevated surface.

Seated Press-Ups

The athlete sits on a bench and grasps onto the front with both hands with the elbows slightly flexed (Fig. 15.43). The athlete raises the body off of the bench by straightening the elbows and pressing down on their hands. This position is held for 2–3 s and then lowered back to the starting position.

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.

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 during these tasks, the amount of knee flexion should be decreased by having the athlete sit up "straighter" against the wall.

ETCH-Swing Forehand, Backhand, Serve

This drill uses the commercially available ETCH-Swing training device (the Etcheberry Experience, Reading, PA). This device is similar to a racket, 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. 15.44). 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 serves.

Fig. 15.44 ETCH-swing forehand (**a**, **b**), backhand (**c**, **d**), serve (**e**, **f**)

Fig. 15.44 (continued)

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. 15.45a). 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. 15.45b.

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. 15.45c).

The medicine ball sideways core toss against the wall exercise is shown in Fig. 15.45d, 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, but 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.

Critical Points

- Eight agility and reaction drills (1–3 per session)
- Seven acceleration, speed, and endurance drills (1–3 per session)
- Six ladders, quick feet, and additional jump drills (1–2 per session)
- Sixteen on-the-court strength training drills (12–14 per session)

Fig. 15.45 Medicine ball-wall exercises. (**a**, **b**) Tennis ball small circles. (**c**) Overhead dribble. (**d**, **e**) Sideways core toss against wall

Results of Programs

Soccer

A prospective study was conducted on 124 female soccer players aged 12–18 years [21]. 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 15.5; see Chap. 13 for test descriptions) indicating a more neutral lower limb alignment on landing. A significant improvement

Table 15.5 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
		Multistage 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	0.2	0.30
		Vertical jump height, 2-step approach (cm)	40.7 ± 8.9	42.1 ± 8.3	1.3	0.04	0.16
		Vertical jump height, counter-movement (cm)	32.9 ± 6.7	32.6 ± 25.8	–0.3	NS	0.02
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
		Multistage fitness test (ml kg^{-1} min^{-1})	34.6 ± 4.5	39.5 ± 5.7	4.9	<0.0001	0.95
		Vertical jump height, counter-movement (cm)	26.2 ± 12.3	28.5 ± 12.0	2.3	<0.0001	0.19
		18-m sprint (s)	3.54 ± 0.30	3.53 ± 0.42	–0.01	NS	0.03
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
		Multistage 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	0.50
		Vertical jump height, counter-movement (cm)	40.1 ± 7.1	41.5 ± 4.5	1.2	0.05	0.24

(continued)

Table 15.5 (continued)

Program	Participants	Test[a]	Pre-train[b]	Post-train[b]	Difference	*P* value	Effect size
Tennis	10 girls	Baseline forehand (no. reps)	8.1 ± 1.0	9.0 ± 0.7	0.9	0.006	1.04
	5 boys	Total distance (m)	40.6 ± 4.7	45.3 ± 3.6	4.6	0.007	1.10
	Aged 11–16 years	Baseline backhand (no. reps)	8.2 ± 0.8	9.0 ± 0.6	0.8	0.0008	1.13
	Tournament, high school players	Total distance (m)	41.3 ± 4.3	45.4 ± 3.0	4.1	0.0009	1.11
		Service line (no. reps)	20 ± 1.8	23.6 ± 2.5	3.6	0.0009	1.84
		Total distance (m)	80.7 ± 8.1	94.1 ± 21.1	13.4	0.003	1.30
		1-Court suicide (s)	20.02 ± 1.48	16.30 ± 1.14	3.73	<0.0001	3.04
		2-Court suicide (s)	100.03 ± 15.31	90.35 ± 10.05	9.68	0.02	0.78
		Abdominal endurance test (s)	92.3 ± 59.0	145.2 ± 62.1	52.9	0.01	0.87
		Single-hop triple crossover hop					
		Right leg (cm)	330.4 ± 71.7	366.7 ± 59.8	36.3	0.05	0.54
		Left leg (cm)	325.7 ± 81.6	361.8 ± 66.2	36.1	0.03	0.50
		Single-leg hop					
		Right leg (cm)	133.8 ± 17.5	139.5 ± 21.1	5.7	NS	0.29
		Left leg (cm)	131.2 ± 23.2	132.9 ± 24.5	1.7	NS	0.08

NS not significant
[a]See Chap. 13 for test descriptions
[b]Mean ± standard deviation

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 multistage 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 to 5.99 ± 0.38 s ($P = 0.02$), the effect size was small (0.30). A significant improvement was found in the 2-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.

Basketball

A prospective study was performed on 57 high school female basketball players aged 14–17 years [22]. 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 15.5). Improvement in the normalized knee separation distance was demonstrated in 91 % of the subjects. A statistically significant improvement was found in the mean estimated VO_2max 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.

Volleyball

A prospective investigation was conducted on 34 high school female volleyball players aged 14–17 years [20]. 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 15.5). A statistically significant improvement was found in the mean VO_2max 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.

Tennis

A prospective study was conducted in 15 competitive junior tennis players (10 girls, 5 boys; mean age, 13.0 ± 1.5 years) [4]. All athletes completed at least 14 of the 18 training sessions. After training, significant improvements were found for the baseline forehand and backhand tests, the service line test, the 1-court and 2-court suicide tests, the abdominal endurance test, and the single-leg crossover hop distance for both legs (Table 15.5). No subject sustained an injury that resulted in loss of time training or that required formal medical attention.

Critical Points

- Soccer: significant improvements:
  – Absolute knee separation distance, mean ankle separation distance on drop-jump test
  – Agility *T*-test
  – Multistage fitness test, VO_2max
  – 37-m sprint, vertical jump (effect sizes small)
- Basketball: significant improvements:
  – Absolute and normalized knee separation distance on drop-jump test
  – Multistage fitness test, VO_2max
  – Vertical jump (effect size small)
- Volleyball: significant improvements:
  – Absolute and normalized knee separation distance on drop-jump test
  – Multistage fitness test, VO_2max
  – Sit-up test
  – Vertical jump test
- Tennis: significant improvements:
  – Agility and speed tests (baseline forehand, backhand; service line, and 1-court and 2-court suicide runs)
  – Abdominal endurance test
  – Single-leg crossover hop for distance test
- No subject sustained an injury that resulted in loss of time training or that required formal medical attention in all studies.

References

1. Alentorn-Geli E, Myer GD, Silvers HJ et al (2009) Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. Knee Surg Sports Traumatol Arthrosc 17(8):859–879
2. Alentorn-Geli E, Myer GD, Silvers HJ et al (2009) Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: mechanisms of injury and underlying risk factors. Knee Surg Sports Traumatol Arthrosc 17(7):705–729
3. Barber-Westin SD, Noyes FR (2009) Decreasing the risk of anterior cruciate ligament injuries in female athletes. In: Noyes FR (ed) Noyes' Knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 428–463
4. Barber-Westin SD, Hermeto AA, Noyes FR (2010) A 6-week neuromuscular training program for competitive junior tennis players. J Strength Cond Res 24(9):2372–2382
5. Beaulieu ML, Lamontagne M, Xu L (2008) Gender differences in time-frequency EMG analysis of unanticipated cutting maneuvers. Med Sci Sports Exerc 40(10):1795–1804
6. Beaulieu ML, Lamontagne M, Xu L (2009) Lower limb muscle activity and kinematics of an unanticipated cutting manoeuvre: a gender comparison. Knee Surg Sports Traumatol Arthrosc 17(8):968–976
7. Benjaminse A, Otten E (2011) ACL injury prevention, more effective with a different way of motor learning? Knee Surg Sports Traumatol Arthrosc 19(4): 622–627
8. Dempsey AR, Lloyd DG, Elliott BC et al (2007) The effect of technique change on knee loads during sidestep cutting. Med Sci Sports Exerc 39(10):1765–1773

9. Dempsey AR, Lloyd DG, Elliott BC et al (2009) Changing sidestep cutting technique reduces knee valgus loading. Am J Sports Med 37(11):2194–2200
10. Ebben WP, Fauth ML, Petushek EJ et al (2010) Gender-based analysis of hamstring and quadriceps muscle activation during jump landings and cutting. J Strength Cond Res 24(2):408–415
11. Foran B (2001) High-performance sports conditioning. Human Kinetics, Champaign
12. Hanson AM, Padua DA, Troy Blackburn J et al (2008) Muscle activation during side-step cutting maneuvers in male and female soccer athletes. J Athl Train 43(2):133–143
13. Koga H, Nakamae A, Shima Y et al (2010) Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. Am J Sports Med 38(11):2218–2225
14. Landry SC, McKean KA, Hubley-Kozey CL et al (2007) Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. Am J Sports Med 35(11):1888–1900
15. Landry SC, McKean KA, Hubley-Kozey CL et al (2007) Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated run and crosscut maneuver. Am J Sports Med 35(11):1901–1911
16. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010
17. McLean SG, Lipfert SW, van den Bogert AJ (2004) Effect of gender and defensive opponent on the biomechanics of sidestep cutting. Med Sci Sports Exerc 36(6):1008–1016
18. McLean SG, Huang X, van den Bogert AJ (2005) Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. Clin Biomech (Bristol, Avon) 20(8):863–870
19. McNair PJ, Prapavessis H, Callender K (2000) Decreasing landing forces: effect of instruction. Br J Sports Med 34(4):293–296
20. Noyes FR, Barber-Westin SD, Smith ST et al (2011) A training program to improve neuromuscular indices in female high school volleyball players. J Strength Cond Res 25(8):2151–2160
21. Noyes FR, Barber-Westin SD, Smith ST et al (2012) A Training Program to Improve Neuromuscular and Performance Indices in Female High School Soccer Players. J Strength Cond Res. Epub ahead of print. doi:10.1519/JSC.0b013e31825423d9. Accessed on Mar 4, 2012
22. Noyes FR, Barber-Westin SD, Smith ST et al (2012) A training program to improve neuromuscular and performance indices in female high school basketball players. J Strength Cond Res 26(3):709–719
23. Onate JA, Guskiewicz KM, Sullivan RJ (2001) Augmented feedback reduces jump landing forces. J Orthop Sports Phys Ther 31(9):511–517
24. Onate JA, Guskiewicz KM, Marshall SW et al (2005) Instruction of jump-landing technique using videotape feedback: altering lower extremity motion patterns. Am J Sports Med 33(6):831–842
25. Sigward SM, Powers CM (2006) The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. Clin Biomech (Bristol, Avon) 21(1):41–48
26. Wilderman DR, Ross SE, Padua DA (2009) Thigh muscle activity, knee motion, and impact force during side-step pivoting in agility-trained female basketball players. J Athl Train 44(1):14–25
27. Zebis MK, Bencke J, Andersen LL et al (2008) The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. Clin J Sport Med 18(4):329–337

ACL Injury Prevention in Soccer: The Santa Monica Experience

16

Holly J. Silvers and Bert R. Mandelbaum

Contents

H.J. Silvers, M.P.T. (✉) • B. R. Mandelbaum, M.D.,
2020 Santa Monica Blvd, 4th Floor,
Santa Monica, CA 90404, USA
e-mail: hollysilverspt@aol.com; bmandelbau@aol.com

Introduction

Soccer is the most widely played sport for both males and females alike. There are approximately 265 million registered players globally, and that number continues to increase, particularly in the female soccer community [17]. In the last 10 years, soccer participation by females has increased by 210 % in the United States, 250 % in Switzerland, and 160 % in Germany [7]. The increase in global participation of the sport has a variety of positive effects on personal health including lower rates of systemic illness and decreased rates of morbid obesity, type II diabetes, and heart disease. In addition to the physical benefits of participation in sport, there has been a concerted effort to combine participation in football with health education in order to promote wellness and health and to prevent the spread of illness and disease. The Federation Internationale de Football Association (FIFA) recently enacted the "Football for Health" campaign for children in South Africa to significantly increase the participants' knowledge in health with respect to preventable noncommunicable diseases [26].

However, with the influx of participation and more athletic exposures being recorded, there is a direct correlation with increased athletic exposure and risk of injury. Numerous studies have documented the risks associated with playing soccer and the epidemiology associated with playing competitively [19, 21, 28, 29, 60, 70]. In the last decade, there has been a global movement to gain a thorough understanding of injuries

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_16, © Springer-Verlag Berlin Heidelberg 2012

associated with soccer participation and the prevention of such injuries [16, 34, 39, 47, 69, 72].

After the passage of Title IX of the Educational Amendments in 1972 in the USA, allowing equal opportunity for female participation in sport, there has been an exponential surge of females participating in organized sports [1]. With this influx in athletic participation, there have also been more injuries sustained by young females between the ages of 13 and 22. Female athletes have a two- to ten-fold higher incidence rate of anterior cruciate ligament (ACL) injuries compared with their male counterparts [50]. Arendt and Dick [2] examined the increased incidence of ACL injury among National Collegiate Athletic Association (NCAA) Division I athletes participating in basketball and soccer over a 5-year period. The average ACL injury rate was 0.31 per 1,000 athlete exposures (AE) for female soccer and 0.29 per 1,000 AE for female basketball. This was compared with 0.13 for male soccer and 0.07 for male basketball per 1,000 AE. The comparison of this epidemiological data points to the obvious disparity in injury rates between genders in younger age groups. However, the data shifts when we analyze older populations. Men over the age of 27 have a greater incidence of ACL injury compared to women in all sports [45]. This may be due to a greater rate in organized and professional sport participation as athletes become older.

ACL injuries can lead to chronic knee pathology, including instability, secondary injury to the menisci and articular cartilage, and the early onset of osteoarthritis. Approximately 66 % of all patients that incur a complete ACL injury also sustain damage to the menisci and the articular cartilage of the femur, patella, and/or tibia. This injury, coupled with the risk of secondary injury, can significantly interfere with the activities of daily living and quality of life. Having a ruptured ACL surgically reconstructed can significantly reduce the risk for secondary injury [24, 32, 39, 57]. Seitz et al. [65] noted that 65 % of ACL-deficient patients sustained a secondary meniscal injury within 2.5 years of the initial date of injury.

Despite the most earnest efforts of orthopedic surgeons to preserve the integrity of the knee joint during ACL reconstructive surgery, individuals with reconstructed ACLs continue to suffer degenerative changes of the articular cartilage and the inevitable early onset of osteoarthritis. Lohmander et al. [44] completed a 12-year longitudinal study to follow up on female athletes that previously underwent ACL reconstruction after sustaining an injury while playing soccer. They found that 55 women (82 %) had radiographic changes in their index knee and 34 (51 %) fulfilled the criterion for radiographic knee osteoarthritis. The mean age for the participants involved with this study was 31. The implications of this research are ominous, hence increasing the need to prevent these injuries from occurring in the first place.

Critical Points

- Soccer is the most highly participated sport by both men and women.
- Women tend to be at greater risk of ACL injury compared to men, particularly under the age of 23.
- Male injury rates for ACL injury tend to increase with age.
- There is a direct correlation between ACL injury and future radiographic knee changes and early onset of osteoarthritis.

Epidemiology of ACL Injury in Soccer

The rate of injury in soccer depends on several factors: age, level of competition, position on the field, setting, location of injury, time of injury, and gender. Injuries incurred during soccer most commonly involve the lower extremities and are usually graded mild to moderate sprains, strains, or contusions [3, 10, 12, 25]. In a study analyzing the injury rates of professional male soccer athletes in the United States, Morgan et al. [52] found that the overall injury rate was 6.2 injuries/1,000 h of participation. Interestingly, the rates were strikingly different when the data was stratified for games and practices: the practice injury rates were 2.9 injuries/1,000 h of participation compared to 35.3 injuries/1,000 h in a game setting. Furthermore, the authors noted that 77 % (197 of 256) of injuries involved the lower extremity, with the knee (*N*=54) and ankle (*N*=46) most frequently affected.

The NCAA recorded injury rates for male and female collegiate soccer players over the course of 15 years [1, 2, 15]. The studies noted that for males, the injury rate was four times higher in games compared with practices (18.75 vs. 4.34 injuries/1,000 AE). In both games and practices, more than two-thirds of men's soccer injuries occurred to the lower extremities, followed by the head and neck during games and the trunk and back in practices. Although player-to-player contact was the primary cause of injury during games, most practice injuries occurred without direct contact to the injured body part. Ankle ligament sprains represented the most common injury during practices and games, whereas knee internal derangements were the most common type of severe injury (defined as ≥10 days of time loss).

On the contrary, when women's collegiate injuries were analyzed, the injury rate was more than three times higher in games than in practices (16.44 vs. 5.23 injuries/1,000 AE). The preseason practices had an injury rate that was more than three times greater than the rate for in-season practices (9.52 vs. 2.91 injuries/1,000 AE). Approximately 70 % of game and practice injuries affected the lower extremities. Ankle ligament sprains (18.3 %), knee internal derangements (15.9 %), concussions (8.6 %), and leg contusions (8.3 %) accounted for most of game injuries reported. However, upper leg muscle-tendon strains (21.3 %), ankle ligament sprains (15.3 %), knee internal derangements (7.7 %), and pelvis and hip muscle strains (7.6 %) accounted for most of the practice injuries reported. Player-to-player contact accounted for approximately 54 % of the game injuries but less than 20 % of all practice injuries. The majority of practice injuries involved noncontact injury mechanisms [15].

In a professional analysis of women's soccer injuries, Junge et al. [40] recorded injuries incurred in seven international soccer tournaments. During the tournaments, 387 injuries were reported during 174 games (incidence of 67.4 injuries/1,000 player hours, 95 % CI 60.7–74.1) or 2.2 injuries/match (95 % CI 2.0–2.4). Most of the injuries (84 %; 317/378) were caused by contact with another player, similar to the game data recorded at the NCAA [1, 15]. The injuries frequently involved the lower extremity (*N*=48; 65 %), followed by the head and neck (*N*=67, 18 %), trunk (*N*=33, 9 %), and upper extremity (*N*=32, 8 %). Contusions (*N*=166; 45 %) were the most frequent type of injury, followed by sprains or ligament rupture (*N*=96; 26 %) and strains or muscle fiber ruptures (*N*=31; 8 %). The most common diagnosis was an ankle sprain. On average, 1 injury/match (95 % CI 0.8–1.2) was expected to result in absence from a match or training. The injury rate in women's top-level tournaments was similar to the range reported for match injuries in elite male and female players. However, the diagnoses and mechanisms of injury among the female players differed substantially from those previously reported in male soccer players [40].

With respect to player position, time of injury, and the frequency of injury, Bailey et al. [4] found that strikers and defenders were most commonly injured, especially those playing in amateur leagues. With regard to the position of the injured player on the field, 8 (54 %) injuries occurred in midfielders, 3 (20 %) each in forward and defense position players, and 1 (7 %) in the goalkeeper. The median age of the injured players was 22 years (range, 20–35 years). In addition, the time of injury during the game was significant. The authors noted that most of the injuries occurred in the fourth quarter, followed by the first quarter and the third quarter of the match, respectively. This data could reinforce the hypothesis that neuromuscular fatigue may play a role in injury risk.

Giza et al. [29] reported data from the first two seasons of the Women's United Soccer Association in order to determine the injury incidence, anatomic location of injuries, and relation of player position. The researchers recorded player position at the time of injury (*N*=168 players). Midfielders sustained the most injuries (*N*=57, 34.1 %) followed by defenders (*N*=47, 28.1 %), strikers (*N*=38, 22.8 %), and goalkeepers (*N*=26, 15.0 %). Compared to all players, midfielders suffered a significantly higher number of injuries ($P < .007$); however, compared to other field players, midfielder injuries did not reach a statistically significant value.

Critical Points

- Midfielders have been statistically shown to sustain higher injury rates than other field players.
- Injury rates in collegiate and professional female players are most often contact in nature.
- The lower extremity is most frequently injured in both game and practice settings.
- Injuries most commonly occur late in the match (last quarter). This could potentially be secondary to neuromuscular and physiological fatigue.

Mechanism of ACL Injury in Soccer

In regard to environmental, anatomic, and hormonal risk factors, there is no conclusive evidence that would indicate any one single risk factor in these respective categories that is directly correlated with an increase in ACL injuries in the female athlete population. They certainly may play a confounding role, and therefore, should not be discounted [14, 18, 22, 23, 27, 30, 31, 33, 53, 57, 59, 63, 64, 66, 68, 73]. However, the emphasis has turned to biomechanical risk factors and the use of neuromuscular and proprioceptive intervention programs to address potential biomechanical deficits [56, 62].

Neuromuscular control is defined as the unconscious efferent response to an afferent signal regarding dynamic joint stability. The afferent proprioceptive signals that elicit motor control can be distinguished by their role: feedback or feedforward. Feedback mechanisms are a result of afferent input (force to the joint) and are reflexive in nature. The time to elicit such a reaction is longer, thus it is thought to be more heavily involved with maintaining posture and slow movement. Feedforward mechanisms are a result of preactivated preparatory activation of muscle [42]. Several research studies have indicated that proprioceptive activities may play a major role in injury reduction [5, 6, 11, 43, 67, 76].

Muscular strength and recruitment patterns are crucial to knee stability. Quadriceps-to-hamstring strength ratios have been examined thoroughly in the literature [56]. The quadriceps serve as an antagonist to the ACL secondary to its attachment site. The quadriceps, upon activation, may increase the anterior shear force on the tibia if it remains unopposed by an antagonist. The hamstrings act as an agonist to the ACL, as they reinforce the ligament by preventing the excessive anterior translation of the tibia. If the hamstrings demonstrate weakness or a delay in contractility from a temporal perspective compared to the quadriceps, the ACL may be at an increased risk for injury and subsequently lead to tensile failure [13, 51].

Landing from a jump with minimal hip and knee flexion increases the ground reaction forces transmitted to the lower extremity and increases the shear force from the activated quadriceps, thus mechanically stressing the ACL [38, 75]. More et al. [51] studied a cadaveric model that incorporated quadriceps and hamstrings muscle loads to simulate the squat exercise. When the hamstring was loaded, anterior tibial translation during flexion was significantly reduced in addition to a reduction in internal tibial rotation during flexion. Hamstrings muscle activity during a squat functions synergistically with the ACL to provide anterior knee stability. McLean et al. [48] compared knee kinematics and gender in 30 high-performance athletes performing side-cutting maneuvers. Women displayed increased intertrial variability for axial internal rotation patterns during cutting compared with men. Gender, however, was not the main determining factor. Instead, the differences in axial rotation were directly related to level of experience. It is important to note that these subjects were high-performance athletes, which might have resulted in a selection bias.

On a follow-up study, McLean et al. [49] studied 10 male and 10 female athletes performing cutting maneuvers with random perturbations at initial contact ($n = 5{,}000$). Injury to the ACL in the sagittal plane was defined as incurring an anterior drawer force greater than 2,000 N. The researchers found that neuromuscular perturbations produced significant increases in external knee anterior force, valgus moments, and internal rotation moments. During the study, the anterior drawer force never exceeded 2,000 N in any model. Valgus loads reached values that were high enough to rupture the ligament, occurring more frequently in females than in males. The researchers concluded that sagittal plane knee joint forces cannot rupture the ACL during sidestep cutting, primarily due to the fact that the muscle and joint mechanics and external ground reaction forces in this plane protect the upward limit of ligament loads. They suggested that valgus loading is a more likely injury mechanism, especially in females [48].

In contrast, Malinzak et al. [46] compared knee-motion patterns in male and female recreational athletes. Three-dimensional coordinates and EMG data were collected for knee flexion-extension, valgus-varus, and internal-external rotation angles. Female athletes demonstrated less knee flexion and greater knee valgus when landing from a jump and with cutting maneuvers. The study also determined that female athletes demonstrated greater quadriceps activity (based on electromyographic analysis) in concert with decreased hamstring activity. In addition, the frequency and intensity of hamstring activity was less in females versus males. Female athletes typically contracted their hamstring fibers 50 ms slower than their male counterparts (200 ms for females vs. 150 ms for males) and with less intensity (55.2 % females vs. 71.8 % in males at initial contact).

When we consider the role of trunk musculature activation with respect to dynamic knee movements, we note how optimal strength of the core is a vital component to injury prevention. Hewett et al. [37] assessed the role of lateral trunk and knee abduction angles during an actual ACL injury. The researchers analyzed video still captures from 23 coronal (10 female, 7 male ACL-injured players and 6 female controls) and 28 sagittal plane videos performing similar landing and cutting tasks. The lateral trunk and knee abduction angles were higher in female compared to male athletes during ACL injury ($P<.05$) and trended toward being greater than the uninjured female controls ($P=.16$ and .13, respectively). Female ACL-injured athletes showed less forward trunk lean than female controls at initial contact ($1.6 \pm 9.3°$ vs. $14.0 \pm 7.3°$, $P=.01$). The researchers noted that female athletes landed with increased lateral trunk motion and knee abduction during an actual ACL injury than did male athletes or uninjured control females during similar landing and cutting tasks.

Brophy et al. [8] analyzed the role of leg dominance with respect to ACL injury and gender in competitive soccer players. The researchers completed a retrospective analysis of 93 (41 male, 52 female) ACL injuries that occurred while playing soccer. Nearly half of the injuries occurred in the dominant kicking leg ($N=30$), while the other half occurred in the contralateral leg ($N=28$). However, when the data was stratified for gender, there was a significant difference in the distribution of noncontact ACL injury; 74.1 % of males (20/27) were injured on the dominant kicking leg compared with 32 % (10/31) of females ($P<.002$). When limited to a noncontact injury mechanism, females were more likely to injure the ACL in their supporting leg, whereas males tend to injure their kicking leg (Table 16.1). This research suggests that limb dominance does serve as an etiological factor with regard to ACL injuries sustained while playing soccer. Future research should investigate the cause for this discrepancy, which could potentially be due to underlying gender-based strength differences and neuromuscular alterations during sport participation.

Critical Points

- Biomechanical assessment of male and female athletes suggests that gender differences do exist.
- Female athletes tend to demonstrate frontal plane deficiencies, whereas males tend to demonstrate sagittal plane deficiencies.
- Female athletes tend to demonstrate decreased hip and knee flexion upon landing from a jump.

Table 16.1 Noncontact ACL injury with respect to gender and leg dominance

		Dominant leg		Noncontact ACL injury	
Gender	*N*	Right	Left	Right	Left
Female (*N*=52)					
Professional	3	2	1	2	2
College	17	16	1	1	5
High school/club	17	16	1	2	7
Youth/recreational	15	13	2	5	7
Total	52	47	5	10	21
Average age (injury): 20.4 ± 7.99				32.26 %	67.74 %
Total noncontact ACL injuries: 31					
Male (*N*=41)					
Professional	12	11	1	5	3
College	6	5	1	5	1
High school/club	4	3	1	2	1
Youth/recreational	19	18	1	7	2
Total	41	37	4	20	7
Average age (injury): 30.6 ± 8.84				74.07 %	25.93 %
Total noncontact ACL injuries: 27					

- Furthermore, females tend to utilize their quad and adductors during landing and cutting maneuvers, which increases the sheer and tensile forces applied to the ACL.
- Female athletes tend to show decreased activation of their hamstring musculature upon landing, take a longer time to reach their peak flexion angle, and land in a more shallow peak flexion angle (decreased hip and knee flexion).

ACL Injury Prevention

ACL injury prevention programs focusing on skiing, basketball, European team handball, and soccer have been performed in the past with results ranging in an overall reduction of severe ACL injuries from 60 to 89 % [20, 23, 41].

Henning and Griffis [35] implemented a prevention study in 2 division I basketball programs over a course of 8 years. The program focused on changing the individual player's kinematic technique, stressing knee and hip flexion upon landing from a jump, using accelerated rounded turns instead of an abrupt or more acute angular turn or cutting cycle, and deceleration with a multistep stop as opposed to a one-step stop deceleration. Henning noted an 89 % reduction in the rate of occurrence of ACL injuries in his intervention group compared to the age- and skill-matched control group.

Caraffa et al. [9] and Cerulli et al. [11] implemented a proprioceptive balance training program using 600 semiprofessional and amateur soccer players in Italy. The study consisted of a 20-min training program divided into five phases of balance training with increasing difficulty. The prospective study was completed over the duration of three complete soccer seasons. The researchers found an incidence rate of 1.15 ACL injuries per team per year in the control group compared with a 0.15 incidence rate in the trained athletes. These ratios demonstrated an overall 87 % decrease in ACL injuries compared to the age- and skill-matched control group.

Hewett et al. [36] completed a prospective analysis of 1,263 male and female soccer, basketball, and volleyball athletes using a 6-week preseason neuromuscular training program. The intervention program consisted of stretching, plyometrics, and weight training with emphasis on proper biomechanical alignment and technique.

The group noted that the incidence of serious knee injury was 2.4–3.6 times higher in the untrained group compared with the trained group. When examining the rate of noncontact ACL injuries, five untrained female athletes sustained ACL injuries (relative injury incidence 0.26), no trained females sustained an ACL injury (0), and one male athlete sustained an ACL injury (0.05).

Ettlinger et al. [20] implemented the "guided discovery" technique in Vermont that focused on avoiding high-risk skiing behavior and positioning (i.e., "phantom foot"), recognizing potentially dangerous skiing situations, and responding quickly to unfavorable conditions. During the 1993–1994 ski season, 4,700 ski instructors and patrollers completed the comprehensive training program at 20 ski areas throughout the United States. As a result, the rate of serious knee injuries decreased by 62 % among the trained individuals compared with those who did not participate in the training program.

Heidt et al. [34] studied 300 female adolescent soccer players between the ages of 14 and 18 years of age over a 1 year period. Forty-two athletes participated in the Frappier Acceleration Training Program, a 7-week preseason training program consisting of strength training, flexibility, sports-specific cardiovascular exercise, plyometrics, and sports-cord drills. The study found that the trained group incurred a lower percentage of ACL injuries (2.4 %) compared with the skill- and age-matched control group (3.1 %).

Myklebust et al. [55] instituted a proprioceptive training program for elite female team handball players. This 5-phase training program consisted of floor exercises, wobble board activities, and a balance mat performed two to three times a week over the course of a 5–7-week preseason session and once a week in season. Fifty-eight teams participated (855 players) in the first season (1999–2000) and 52 teams (850 players) participated in the second season (2000–2001). Sixty teams (942 players) in the 1998–1999 season served as the control. There were 29 ACL injuries in the control season, 23 ACL injuries in the first intervention season, and 17 injuries in the second intervention season.

Wedderkopp et al. [74] conducted a randomized controlled trial in 16 European team handball squads. The intervention, similar to Caraffa and Cerulli's intervention, used an ankle disc for proprioceptive training. The control group demonstrated significantly higher number of traumatic injuries (16 vs. 6). The incidence of traumatic injuries in the intervention group was 2.4 (95 % CI 0.7; 6.2) injuries per 1,000 game hours and 0.2 (95 % CI 0.02; 0.7) injuries per 1,000 practice hours. In the control group, the incidence was 6.9 (95 % CI 3.3; 12.7) injuries per 1,000 game hours and 0.6 (95 % CI 0.2; 1.3) injuries per 1,000 practice hours. A significantly higher multivariate odds ratio (4.8) was found in the group not using the ankle disc. The intervention group had significantly fewer moderate and major injuries.

Critical Points

- Several researchers have demonstrated a significant reduction in ACL injury by virtue of participation in a structured neuromuscular training program.
- The utilization of proprioceptive balance equipment does not seem to positively or negatively affect the efficacy of such programs on injury rates.
- When designing such a program, you must consider the time required, the equipment necessary, and cost associated with an intervention program. All of these factors may directly impact the level of compliance necessary to impart a positive benefit to the athlete.

The Santa Monica Experience: ACL Injury Prevention

Mandelbaum et al. [47] developed the Santa Monica Prevent Injury and Enhance Performance (PEP) ACL program in 2000 to address the high incidence of ACL injuries that was being reported throughout the literature in female soccer players. This program was developed to address the major clinical deficits that were fairly ubiquitous among

ACL-injured athlete. The program was used with 2 age cohorts: 14–18-year-old female club soccer players and 18–22-year-old female soccer athletes participating in division I NCAA soccer. The program consisted of a 20-min dynamic warm-up protocol that preceded the normal soccer training session or competitive game.

During the first year of the study, a total of 2 ACL tears, confirmed by magnetic resonance imaging, were reported for the intervention group. This translated to an incidence rate of 0.05 ACL injuries per 1,000 AE. Thirty-two ACL tears were reported for the control group: an incidence rate of 0.47 ACL injuries per 1,000 AE. These results translated to an 88 % overall reduction of ACL injury compared to an age- and skill-matched control group. During the second year of the study, 4 ACL tears were reported in the intervention group, with a corresponding incidence rate of 0.13 injuries per 1,000 AE. Thirty-five ACL tears were reported in the control group, with an incidence rate of 0.51 injuries per 1,000 AE. This corresponded to an overall reduction of 74 % in the intervention group compared with an age- and skill-matched control group.

During a collaborative effort between the Santa Monica Sports Research Foundation and the Centers for Disease Control (CDC), the prior study was followed by a randomized, controlled trial using the PEP Program in Division I NCAA Women's Soccer Teams [28]. Sixty-one teams with 1,429 athletes completed the study; participating athletes were divided into 854 athletes on 35 control teams and 575 athletes on 26 intervention teams. No significant differences were noted between intervention and control athletes with regard to age, height, weight, or history of past ACL injuries. After using the PEP program during one season, there were 7 ACL injuries in the intervention athletes (IA) compared with 18 in control athletes (CA), 0.14 versus 0.25 ($P = .15$). There were no ACL injuries reported in IA during practices compared with 6 in CA (0.10; $P = .01$). Noncontact ACL injuries in the CA group occurred at over 3 times the rate of the IA group (0.14 vs. 0.04; $P = .06$). Control athletes with a prior history of ACL injury suffered a reoccurrence 5 times more frequently than the IA group (0.10 vs. 0.02; $P = .06$); this difference reached significance when limited to noncontact ACL injuries during the season (0.06 vs. 0.00; $P < .05$). There was a significant difference in the rate of ACL injuries in the second half of the season (weeks 6–11; IA 0.00 vs. CA 0.18, $P < .05$). This would support the concept that it takes approximately 6–8 weeks for a biomechanical intervention program to impart a neuromuscular effect.

Pfeiffer et al. [61] 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 1,439 athletes (862 in the control group and 577 in the treatment group) were monitored. There were 6 confirmed noncontact ACL injuries: 3 in the intervention group and 3 in the control group. The incidence of noncontact ACL injuries was 0.167 per 1,000 exposures in the intervention group and 0.078 in the control group, yielding an odds ratio of 2.05 ($P > .05$). 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.

Critical Points

- The PEP Program is a dynamic warm-up designed to address the deficits most commonly seen in ACL-injured athletes.
- The program should be completed in its entirety and prior to training or a game in a non-fatigued state. When two elements of the program were tested post-training, the effects of the intervention were nullified.
- The program can be initiated in youth athletes over the age of 8 years old.
- 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.

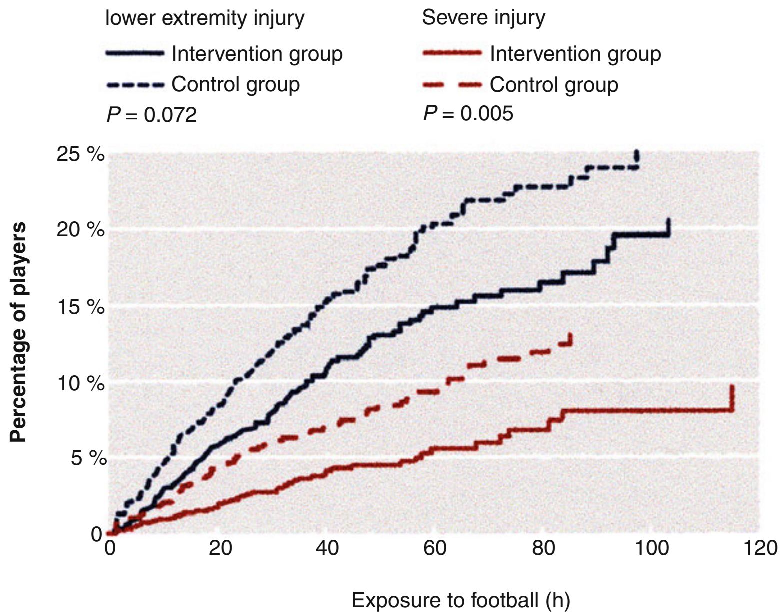


Fig. 16.1 Survival curves based on Cox regression for players with lower extremity injury and severe injury [71]

Analysis of the Efficacy of the FIFA 11+ Program

The Oslo Sports Trauma Research Center also attempted to reduce the incidence of ACL injuries in Norway by using an intervention program known as the "FIFA 11" [72]. A cluster-randomized controlled design was used to test the efficacy of the "11" on injury risk in female soccer players (IA, 59 teams, $N=1{,}091$) compared with a control group (CA, 54 teams, $N=1{,}001$). The "11" was a 15-min warm-up program for core stability, lower extremity strength, neuromuscular control, and agility used over an 8-month season.

A total of 396 players (20 %) sustained 483 injuries. There was no difference in the overall injury rate between the IA (3.6 injuries/1,000 h, confidence interval (CI) 3.2–4.1) and CA (3.7, CI 3.2–4.1; RR = 1.0, CI 0.8–1.2; $P=.94$) or in the incidence for any type of injury. The training program was used during 60 % of the soccer training sessions in the first half of the season, but only 14 out of 58 intervention teams completed more than 20 prevention training sessions. The researchers noted no effect of the injury prevention program on the injury rate secondary to the exercises, perhaps, not being specific enough to address the biomechanical deficiencies present in this population and the low compliance with the program.

To address the issue of decreased compliance and, perhaps, some of the deficits of the content initially selected for the "11" protocol, the Oslo researchers collaborated with FIFA and the Santa Monica Sports Research Foundation. The researchers reconvened, restructured, and renamed the program to the "FIFA 11+." Soligard et al. [71] completed a cluster, randomized controlled trial in 125 soccer clubs from the south, east, and middle of Norway: 65 clusters in the intervention group (IA) and 60 in the control group (CA) followed the protocol for one league season (8 months). There were 1,892 female players ages 13–17 (1055 IA; 837 CA). A comprehensive warm-up program (11+) was used to improve strength, awareness, and neuromuscular control during static and dynamic movements.

During the season, 264 players had relevant injuries: 121 players in the intervention group and 143 in the control group (rate ratio 0.71, 95 % confidence interval 0.49–1.03). In the intervention group, there was a significantly lower risk of injuries overall (0.68, 0.48–0.98), overuse injuries (0.47, 0.26–0.85), and severe injuries (0.55, 0.36–0.83). Though the primary outcome of reduction in lower extremity injury did not reach statistical significance, the risk of severe injuries, overuse injuries, and injuries overall was reduced (Fig. 16.1). In addition, the intervention groups that performed the program more often reaped the benefit of lower injury rates overall.

The risk of injury was 35 % lower in intervention players in the highest third of compliance (2.6 [20. to 3.2] injuries/1,000 player hours, mean 49.2 [range 33–95] sessions). This was compared to players in the intermediate third (4.0 [3.0–5.0] injuries/1,000 player hours, mean 23.4 [range, 15–32] sessions) (rate ratio 0.65, 0.44–0.94, $P = .02$). The 32 % reduction in risk of injury compared with the third with the lowest compliance (3.7 (2.2–5.3) injuries/1,000 player hours, mean 7.7 [range, 0–14] sessions) did not reach significance (rate ratio 0.68, 0.41–1.12, $P = .13$). There was an inverse correlation between compliance and injury rates. The study indicated that a structured warm-up program can prevent injuries in young female soccer players.

An emphasis on proper landing technique; landing softly on the metatarsal heads and rolling back to the rearfoot; engaging in knee and hip flexion upon landing from a jump or header and during lateral (cutting) maneuvers; avoiding excessive genu valgum at the knee upon landing and squatting; increasing hamstring, gluteus medius, and hip abductor strength; and addressing proper deceleration techniques are activities that are inherent in each of the aforementioned ACL prevention protocols (Figs. 16.2, 16.3, and 16.4).

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 FIFA 11+ program. The program has demonstrated a significant decrease in all lower extremity injury rates and time loss secondary to injury.
- 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 20 min to complete and does not require additional equipment.

Fig. 16.2 Russian hamstring

Future Directions

The growth and popularity of the sport of soccer is unprecedented. It infiltrates nearly every community in a global fashion. The benefits of sport participation are numerous and far outweigh the risks. However, the likelihood of incurring a soccer-related injury should not be underestimated. As clinicians, it is integral to our collective ethos to recognize the risks associated with the game of soccer and to profess the merits of prevention protocols like those cited in the peer-reviewed literature.

The literature on ACL injury prevention has consistently found that a neuromuscular training program may significantly reduce

Fig. 16.3 Bounding agility run

the incidence of ACL injuries in the female and male soccer athlete [9, 11, 20, 28, 30, 31, 36, 47, 54, 55, 71, 72]. A prophylactic training program that focuses on developing and improving neuromuscular control of the lower extremity though strengthening exercises, plyometrics, and sport-specific agilities may address the proprioceptive and biomechanical deficits and pathokinematics that high-risk female and male athletes tend to demonstrate. Future studies should strive to identify which of the components of present-day prevention programs are most significant in decreasing the rate of noncontact ACL injuries.

These studies demonstrate the critical need for further randomized clinical trials on the relevance of fatigue with respect to injury, age, gender, role of early sport specificity, and the timing of the implementation of a neuromuscular injury prevention program [58, 61]. Researchers should continue to seek innovative ways of improving the quality and efficacy of existing prevention programs within each sporting community and recognize and embrace the need for further randomized controlled trials to further elucidate the epidemiology, etiology, mechanism of injury, and, ultimately, the prevention of sports-related ACL injury.

Fig. 16.4 Single-leg eccentric squat

References

1. Agel J, Arendt EA, Bershadsky B (2005) Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. Am J Sports Med 33(4):524–530
2. Arendt E, Dick R (1995) Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. Am J Sports Med 23(6):694–701
3. Azubuike SO, Okojie OH (2009) An epidemiological study of football (soccer) injuries in Benin City, Nigeria. Br J Sports Med 43(5):382–386
4. Bailey R, Erasmus L, Luttich L et al (2009) Incidence of injuries among male soccer players in the first team of the University of the Free State in the Coca Cola League – 2007/2008 season. S Afr J Sports Med 21(1):3–6
5. Besier TF, Lloyd DG, Cochrane JL et al (2001) External loading of the knee joint during running and cutting maneuvers. Med Sci Sports Exerc 33(7):1168–1175
6. Bjordal JM, Arnoy F, Hannestrad B et al (1997) Epidemiology of anterior cruciate ligament injuries in soccer. Am J Sports Med 25(3):341–345
7. Blatter JS (2007) FIFA's injuries to women. Health and fitness for the female football player: a guide for players and coaches. http://www.fifa.com/aboutfifa/footballdevelopment/medical/index.html. Federation Internationale de Football Association, Switzerland
8. Brophy R, Silvers HJ, Gonzales T et al (2010) Gender influences: the role of leg dominance in ACL injury among soccer players. Br J Sports Med 44(10):694–697
9. Caraffa A, Cerulli G, Projetti M et al (1996) Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. Knee Surg Sports Traumatol Arthrosc 4(1):19–21
10. Center DCaP (2000) Nonfatal sports- and recreation-related injuries treated in emergency departments – USA, July 2000–June 2001. MMWR, vol 51. Centers for Disease Control and Prevention
11. Cerulli G, Benoit DL, Caraffa A et al (2001) Proprioceptive training and prevention of anterior cruciate ligament injuries in soccer. J Orthop Sports Phys Ther 31(11):655–660; discussion 661
12. Chandy TA, Grana WA (1985) Secondary school athletic injury in boys and girls: a three-year comparison. Physician Sportsmed 13(3):106–111

13. Decker MJ, Torry MR, Noonan TJ et al (2002) Landing adaptations after ACL reconstruction. Med Sci Sports Exerc 34(9):1408–1413
14. Deppen RJ, Landfried MJ (1994) Efficacy of prophylactic knee bracing in high school football players. J Orthop Sports Phys Ther 20(5):243–246
15. Dick R, Putukian M, Agel J et al (2007) Descriptive epidemiology of collegiate women's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988–1989 through 2002–2003. J Athl Train 42(2):278–285
16. Dvorak J, Junge A (2005) F-MARC football medicine manual: 1994–2005. Federation Internationale de Football Association, Switzerland
17. Dvorak J, Junge A (2005) Preface. In: F-MARC football medicine manual. Federation Internationale de Football Association, Switzerland, pp 1994–2005
18. Ekstrand J, Nigg BM (1989) Surface-related injuries in soccer. Sports Med 8(1):56–62
19. Engstrom B, Johansson C, Tornkvist H (1991) Soccer injuries among elite female players. Am J Sports Med 19(4):372–375
20. Ettlinger CF, Johnson RJ, Shealy JE (1995) A method to help reduce the risk of serious knee sprains incurred in alpine skiing. Am J Sports Med 23(5):531–537
21. Faude O, Junge A, Kindermann W et al (2005) Injuries in female soccer players: a prospective study in the German national league. Am J Sports Med 33(11):1694–1700
22. Feagin JA Jr, Lambert KL (1985) Mechanism of injury and pathology of anterior cruciate ligament injuries. Orthop Clin North Am 16(1):41–45
23. Feagin JA Jr, Lambert KL, Cunningham RR et al (1987) Consideration of the anterior cruciate ligament injury in skiing. Clin Orthop Relat Res 216:13–18
24. Fetto JF, Marshall JL (1980) The natural history and diagnosis of anterior cruciate ligament insufficiency. Clin Orthop Relat Res 147:29–38
25. Fuller CW, Junge A, Dvorak J (2005) A six year prospective study of the incidence and causes of head and neck injuries in international football. Br J Sports Med 39(Suppl 1):i3–i9
26. Fuller CW, Junge A, DeCelles J et al (2010) 'Football for Health' – a football-based health-promotion programme for children in South Africa: a parallel cohort study. Br J Sports Med 44(8):546–554
27. Galey S, Arnold CM, Konieczko E et al (2000) Immunohistochemical identification of relaxin receptors on anterior cruciate ligaments. In: Annual meeting of the Orthopaedic Research Society, ORS, 2000, p 794
28. Gilchrist J, Mandelbaum BR, Melancon H et al (2008) A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. Am J Sports Med 36(8):1476–1483
29. Giza E, Mithofer K, Farrell L et al (2005) Injuries in women's professional soccer. Br J Sports Med 39(4):212–216; discussion 212–216
30. Griffin LY, Agel J, Albohm MJ et al (2000) Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. J Am Acad Orthop Surg 8(3):141–150
31. Griffin LY, Albohm MJ, Arendt EA et al (2006) Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. Am J Sports Med 34(9):1512–1532
32. Harner CD, Paulos LE, Greenwald AE et al (1994) Detailed analysis of patients with bilateral anterior cruciate ligament injuries. Am J Sports Med 22(1):37–43
33. Heidt RS Jr, Dormer SG, Cawley PW et al (1996) Differences in friction and torsional resistance in athletic shoe-turf surface interfaces. Am J Sports Med 24(6):834–842
34. Heidt RS Jr, Sweeterman LM, Carlonas RL et al (2000) Avoidance of soccer injuries with preseason conditioning. Am J Sports Med 28(5):659–662
35. Henning CE, Griffis ND (1990) Injury prevention of the anterior cruciate ligament (videotape). Mid-American Center for Sports Medicine, Wichita
36. Hewett TE, Lindenfeld TN, Riccobene JV et al (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27(6):699–706
37. Hewett TE, Torg JS, Boden BP (2009) Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. Br J Sports Med 43(6):417–422
38. Huston LJ, Vibert B, Ashton-Miller JA et al (2001) Gender differences in knee angle when landing from a drop-jump. Am J Knee Surg 14(4):215–219
39. Jacobson I, Tegner Y (2006) Injuries among female football players – with special emphasis on regional differences. Adv Physiother 8:66–74
40. Junge A, Dvorak J (2007) Injuries in female football players in top-level international tournaments. Br J Sports Med 41(Suppl 1):i3–i7
41. Kirkendall DT, Garrett WE Jr (2000) The anterior cruciate ligament enigma. Injury mechanisms and prevention. Clin Orthop 372:64–68
42. Lephart SM, Riemann BL, Fu FH (2000) Introduction to the sensorimotor system. In: Lephart SM, Fu FH (eds) Proprioception and neuromuscular control in joint stability. Human Kinetics, Champaign, pp xvii–xxiv
43. Lloyd DG (2001) Rationale for training programs to reduce anterior cruciate ligament injuries in Australian football. J Orthop Sports Phys Ther 31(11):645–654; discussion 661
44. Lohmander LS, Ostenberg A, Englund M et al (2004) High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum 50(10):3145–3152
45. Maletis GB, Granan LP, Inacio MC et al (2011) Comparison of community-based ACL reconstruction registries in the U.S. and Norway. J Bone Joint Surg Am 93(Suppl 3):31–36
46. Malinzak RA, Colby SM, Kirkendall DT et al (2001) A comparison of knee joint motion patterns between men and women in selected athletic tasks. Clin Biomech (Bristol, Avon) 16(5):438–445

47. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010
48. McLean SG, Neal RJ, Myers PT et al (1999) Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. Med Sci Sports Exerc 31(7):959–968
49. McLean SG, Huang X, Su A et al (2004) Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. Clin Biomech (Bristol, Avon) 19(8):828–838
50. Miyasaka KC, Daniel DM, Stone ML et al (1991) The incidence of knee ligament injuries in the general population. Am J Knee Surg 4(1):3–8
51. More RC, Karras BT, Neiman F et al (1993) Hamstrings-an anterior cruciate ligament protagonist: an in vitro study. Am J Sports Med 21:231–237
52. Morgan BE, Oberlander MA (2001) An examination of injuries in major league soccer. The inaugural season. Am J Sports Med 29(4):426–430
53. Muneta T, Takakuda K, Yamamoto H (1997) Intercondylar notch width and its relation to the configuration and cross-sectional area of the anterior cruciate ligament. A cadaveric knee study. Am J Sports Med 25(1):69–72
54. Myklebust G, Maehlum S, Holm I et al (1998) A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. Scand J Med Sci Sports 8(3):149–153
55. Myklebust G, Engebretsen L, Braekken IH et al (2003) Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. Clin J Sport Med 13(2):71–78
56. Nisell R (1985) Mechanics of the knee. A study of joint and muscle load with clinical applications. Acta Orthop Scand Suppl 216:1–42
57. Olsen OE, Myklebust G, Engebretsen L et al (2003) Relationship between floor type and risk of ACL injury in team handball. Scand J Med Sci Sports 13(5):299–304
58. Olsen OE, Myklebust G, Engebretsen L et al (2005) Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. BMJ 330(7489):449
59. Orchard JW, Powell JW (2003) Risk of knee and ankle sprains under various weather conditions in American football. Med Sci Sports Exerc 35(7):1118–1123
60. Ostenberg A, Roos H (2000) Injury risk factors in female European football. A prospective study of 123 players during one season. Scand J Med Sci Sports 10(5):279–285
61. Pfeiffer RP, Shea KG, Roberts D et al (2006) Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. J Bone Joint Surg Am 88(8):1769–1774
62. Sainburg RL, Poizner H, Ghez C (1993) Loss of proprioception produces deficits in interjoint coordination. J Neurophysiol 70(5):2136–2147
63. Samuel CS, Butkus A, Coghlan JP et al (1996) The effect of relaxin on collagen metabolism in the nonpregnant rat pubic symphysis: the influence of estrogen and progesterone in regulating relaxin activity. Endocrinology 137(9):3884–3890
64. Sciore P, Frank CB, Hart DA (1998) Identification of sex hormone receptors in human and rabbit ligaments of the knee by reverse transcription-polymerase chain reaction: evidence that receptors are present in tissue from both male and female subjects. J Orthop Res 16(5):604–610
65. Seitz H, Marlovits S, Wielke T et al (1996) Meniscus lesions after isolated anterior cruciate ligament rupture. Wien Klin Wochenschr 108(22):727–730
66. Shelbourne KD, Davis TJ, Klootwyk TE (1998) The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears. A prospective study. Am J Sports Med 26(3):402–408
67. Silvers HJ, Mandelbaum BR (2001) Preseason conditioning to prevent soccer injuries in young women. Clin J Sport Med 11(3):206
68. Slauterbeck J, Clevenger C, Lundberg W et al (1997) Effects of estrogen level on the tensile properties of the rabbit anterior cruciate ligament. In: Paper presented at the annual meeting Orthopaedic Research Society, San Francisco, 1997
69. Soderman K, Werner S, Pietila T et al (2000) Balance board training: prevention of traumatic injuries of the lower extremities in female soccer players? A prospective randomized intervention study. Knee Surg Sports Traumatol Arthrosc 8(6):356–363
70. Soderman K, Adolphson J, Lorentzon R et al (2001) Injuries in adolescent female players in European football: a prospective study over one outdoor soccer season. Scand J Med Sci Sports 11(5):299–304
71. Soligard T, Myklebust G, Steffen K et al (2008) Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. BMJ 337:a2469
72. Steffen K, Myklebust G, Olsen OE et al (2008) Preventing injuries in female youth football – a cluster-randomized controlled trial. Scand J Med Sci Sports 18(5):605–614
73. Torg JS, Quedenfeld TC, Landau S (1974) The shoe-surface interface and its relationship to football knee injuries. J Sports Med 2(5):261–269
74. Wedderkopp N, Kaltoft M, Holm R et al (2003) Comparison of two intervention programmes in young female players in European handball – with and without ankle disc. Scand J Med Sci Sports 13(6):371–375
75. Wojtys EM, Huston LJ, Lindenfeld TN et al (1998) Association between the menstrual cycle and anterior cruciate ligament injuries in female athletes. Am J Sports Med 26(5):614–619
76. Yu WB, Kirkendall DT, Garrett WE Jr (2002) Anterior cruciate ligament injuries in female athletes: anatomy, physiology, and motor control. Sports Med Arthrosc Rev 10(1):58–68

ACL Injury Prevention Warm-up Programs

17

Frank R. Noyes and Sue D. Barber-Westin

Contents

F.R. Noyes, M.D.
Cincinnati Sportsmedicine and Orthopaedic Center, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

S.D. Barber-Westin, B.S. (✉)
Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA
e-mail: sbwestin@csmref.org

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 [1–3, 6–9, 11–13, 15–23]. 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 ACL injury rates (Table 17.1) [1, 6, 12, 13, 15–17, 20, 22], athletic performance indicators, or neuromuscular factors (Table 17.2) [2, 3, 7–9, 11, 18, 19, 21, 23]. The goal is to determine if a recommendation may be made from the available

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_17,

Table 17.1 Effect of ACL injury prevention warm-up programs on injury rates in female athletes

Citation Program	No. athletes Type sports No. seasons	Duration of training	Program components	Compliance	Total no. exposures		Number ACL injuries (per 1,000 athlete-exposures)			Comments, study limitations
					Trained	Control	Trained	Control	*P* value	
Myklebust [13]	1,705 trained, 942 control Team handball 3 seasons: 1 control, 2 intervention	15 min, 3×/wk preseason (5–7 wk), 1×/wk during season	Balance board, agility, plyometrics (Table 17.3)	1st season: 26 % teams completed > 15 sessions 2nd season: 29 % teams completed > 15 sessions	1st season: 172,692 2nd season: 186,805	208,936	23 (0.13) 17 (0.09)	29 (0.14)	0.62 0.15	Not randomized, poor compliance with training, noncontact ACL injury rate not provided, insufficient statistical power for ACL noncontact injuries
Petersen [16]	134 trained, 142 control Team handball Adult 1 season	10 min, 3×/wk preseason (8 wk), 1×/wk during season	Balance board, plyometrics (Table 17.4)	NA	NA	NA	1 (0.04)	5 (0.21)	NS	Not randomized, total number of exposures not provided, insufficient statistical
Mandelbaum [12] PEP	1,885 trained, 3,818 control Soccer 14–17 yr 2 seasons	20 min all practices during season	Plyometrics, strength, agility (Table 17.5)	NA	67,860	137,447	6 (0.09)	67 (0.49)	<.0001	Not randomized, voluntary enrollment training, compliance with training not provided
Gilchrist [6] PEP	583 trained, 852 control Soccer, Collegiate 1 season	20 min all practices during season	Plyometrics, strength, agility (Table 17.5)	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
Pfeiffer [17] 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 17.6)	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

Pasanen [15]	256 trained, 201 control Floorball teams Mean 24.2 ± 5 yr 1 season	20–30 min, 1–3×/wk during season	Agility, balance, plyometrics, strength, flexibility (Table 17.7)	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
Steffen [22] The "11"	1,073 trained, 947 control Soccer Under-17 league 1 season	15 min 3×/wk during season	Plyometrics, strength, agility, balance (Table 17.8)	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
Soligard [20] The "11+"	1,055 trained, 837 control Soccer 13–17 yr 1 season	20 min all practices during season	Plyometrics, strength, agility, balance (Table 17.9)	Mean no. sessions: 44 (77 %) during season	49,899	45,428	NA	NA	NA	ACL injury numbers/ rates not given. No significant difference rate of noncontact
LaBella [10] KIPP	485 trained, 370 control Basketball, soccer High school 1 season	20 min all practices during season	Plyometrics, strength, agility (Table 17.13)	NA	20,345	12,467	2 (0.10)	6 (0.49)	.04	Injuries not sorted according to sport, only 37 % of coaches invited participated

PEP Prevent Injury and Enhance Performance program, *KLIP* knee ligament injury prevention program, *KIPP* Knee Injury Prevention Program, *wk* week, *min* minutes

Table 17.2 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
Holm [8] 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 ($P=.003$) 1-leg static balance, 3 hop tests: no increase	NA
Irmischer [9] KLIP College students, active Trained ($n=14$) Control ($n=14$)	20 min, 2×/wk during season	NA	No improvement	NA	NA	Drop-jump: decreased peak vertical impact forces 5.3 ± 1.0 to 3.9 ± 0.6 bw ($P=.0004$), rate force development 0.11 ± 0.03 to 0.08 ± 0.02 bw/ms ($P=.02$)
Grandstrand [7] WIPP Soccer 9–12 yr Trained (n = 12) Control (n = 9)	20–25 min, 2×/wk during season	NA	No improvement	NA	NA	Drop-jump: no improvement
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, shooting distance: no improvement	NA	Countermovement & vertical jumps: no improvement knee valgus angle
Lim [11] PEP, modified Basketball High school Trained (n = 11) Control (n = 11)	20 min all practices during season	Increased peak torque hip abductors 2.80 ± .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($P<.05$), hamstrings-quadriceps ratio 75.09 ± 5.69 to 67.97 ± 4.18 % ($P=.02$)	No improvement	NA	NA	Rebound jump: improved knee flexion angle 92.66 ± 4.34° to 94.27 ± 3.44° ($P=.02$), knee separation distance 17.56 ± 2.92 to 20.81 ± 1.37 cm ($P=.004$), knee extension torque 236.96 ± 39.03 to 192.18 ± 12.37 ($P=.04$) No improvement knee internal rotation angle, knee abduction torque

Pollard [18] 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* = .01), increased hip abduction −4.9 ± 4.0° to −7.7 ± 4.7° (*P* = .02) No difference knee valgus, knee flexion angles
Vescovi [23] 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, pro-agility tests: 2–4 % decline	NA	NA
Sigward [19] PEP Soccer 9–17 yr Trained (*n* = 48)	20 min, 2×/wk during season	NA	NA	NA	NA	Reactive side-step cut: reduced peak knee valgus moment 0.49 to 0.56 Nm/kg·cm (*P* = .02)
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* < .001)	NA	Single-legged timed hop: improved right leg 2.17 ± 0.4 to 2.03 ± 0.3 s (*P* < .001), left leg 2.17 ± 04. to 2.0 ± 0.2 s (*P* < .001)	Drop-jump: increased knee flexion foot strike 29.9 ± 9.0 to 35.1 ± 7.4° (*P* = .003) & stance phase 81.3 ± 10.5 to 86.9 ± 10.3° (*P* = .006), decreased peak knee flexion moment 0.739 ± 0.37 to 0.583 ± 0.30 N·m (*P* = .04). No improvement 21 other factors. Stop jump: decreased hip flexion 72.2 ± 11.0 to 68.0 ± 8.9°(*P* = .05), maximum hip external rotation 20.0 ± 12.5 to 13.1 ± 13.8° (*P* = .02), dynamic knee valgus 0.863 ± 0.37 to 0.734 ± 0.31 N·m (*P* = .04). No improvement 21 other factors

(continued)

Table 17.2 (continued)

Citation Program Subjects	Duration training	Strength	Vertical jump	Speed, agility	Limb symmetry, balance	Neuromuscular indices
DiStefano [3] General and stratified ACL injury programs Soccer 10–17 yr Trained ($n = 90$ males, 83 females)	10–15 min, 3–4×/wk during season	NA	NA	NA	NA	Drop-jump: subjects with landing technique poor at baseline improved technique more than others High school aged improved greater than pre-high school No differences in change in landing technique after training between programs or sexes

[a]All studies included only female athletes unless otherwise indicated

KLIP knee ligament injury prevention program, *WIPP* Warm-up for Injury Prevention and Performance, *PEP* Prevent Injury and Enhance Performance, *NA* not assessed, *BW* body weight, *MS* meters per second, *wk* week, *min* minutes peer-reviewed literature to date on the usage of these types of programs. Only articles which focused on female athletes are included.

Critical Points

- ACL injury prevention warm-up programs: handball, soccer, basketball, volleyball, floorball
- Potential advantages: improved compliance, decreased fatigue
- Possible disadvantages: failure to improve neuromuscular deficits, athletic performance tests, noncontact ACL injury rate

Programs: Components and Results

Myklebust Program

Myklebust et al. [13] designed a 3-part program comprised of balance, plyometric, and agility exercises for female team handball players (Table 17.3). The program, supervised by physical therapists, was performed 3×/week for 5–7 weeks before the start of the season and then 1×/week during the season. There were 942 athletes in the control group (1998–1999 season) and 1,705 in the intervention group (2 seasons: 1999–2001) from the top 3 divisions of the Norwegian Handball Federation.

Overall, there was no significant reduction in the ACL injury rate between the control (0.15 per 1,000 athlete-exposures) and both intervention seasons (0.13 and 0.09 per 1,000 athlete-exposures, seasons 1 and 2, respectively). 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, Myklebust et al. found that 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 athlete-exposures 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. In addition, compliance was a major issue and was considered to be required for the intervention to be successful in reducing ACL injury incidence rates.

Holm et al. [8] conducted an investigation regarding the effectiveness of this program in improving static and dynamic balance, proprioception, strength, and single-legged hop test performance in 27 elite team handball players. The players had participated in the Myklebust study and underwent a series of tests before starting the intervention program and then again at the end of the season. There was a significant improvement in 2-legged dynamic balance assessed using a KAT 2000 (OEM Medical, Carlsbad, CA) moveable platform device (balance index score, 924 ± 225 vs. 778 ± 714, $P = .003$). However, there were no significant increases in single-legged static balance, proprioception, isokinetic lower extremity muscle strength, or distance hopped on single-legged function tests.

Petersen Program

Petersen et al. [16] 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 17.4), was conducted 3×/week during the preseason for 8 weeks, and then 1×/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 1,000 athlete-exposures, respectively). The 5 ACL ruptures in the control group were caused by a noncontact mechanism, while the 1 ACL rupture in the intervention group was sustained by direct trauma.

Table 17.3 Myklebust program [13]

Floor exercises Week 1: Running & planting with partner running backwards & 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 & finishing with a 2-ft landing with flexion in both hips and knees Week 3: Running and planting (as in wk 1) with full plant & cut movement with ball, focusing on knee position Week 4: 2 and 2 players together, 2-leg jump forward & backwards, 180° turn & the same movement backwards; partner tries to push the player out of control, focus on landing technique Week 5: Expand movement from wk 3 to full plant & cut, 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 hip & knees Week 3: "Step" down from box with 1-leg landing with flexion in hip & knee Week 4: 2 players both standing on balance mats trying to push partner out of balance, first on 2 legs, 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, then on 1 leg

Table 17.4 Petersen handball injury prevention program [16]

Phase	Balance board exercises	Jump exercises
I	Single-legged 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-legged 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-legged 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-legged 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-legged 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-legged 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

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. The authors concluded that the program showed promising, although not statistically significant, trends in preventing lower extremity injuries.

Prevent Injury and Enhance Performance (PEP) Program

Mandelbaum et al. [12] designed the Prevent Injury and Enhance Performance program (PEP) warm-up for female soccer players. The program consisted of 3 basic warm-up activities,

Table 17.5 Prevent Injury and Enhance Performance Program (PEP) [12]

Exercise	Distance	Duration
1. Warm-up		
Jog line to line	45.7 m	1 rep
Shuttle run	45.7 m	1 rep
Backward running	45.7 m	1 rep
2. Stretching		
Calf	NA	2 × 30 s
Quadriceps	NA	2 × 30 s
Hamstring	NA	2 × 30 s
Inner thigh	NA	2 × 30 s
Hip flexor	NA	2 × 30 s
3. Strengthening		
Walking lunges	18.3 m	2 passes
Russian hamstring	NA	30 s
Single-toe raise	NA	30, bilaterally
4. Plyometrics		
Lateral hops	5.08–5.24 cm cone	30 s
Forward hops	5.08–5.24 cm cone	30 s
Single-legged hops	5.08–5.24 cm cone	30 s
Vertical jumps	NA	30 s
Scissors jumps	NA	30 s
5. Agilities		
Shuttle run	36.6 m	1 rep
Diagonal run	36.6 m	1 rep
Bounding run	36.6–45.7 m	1 rep

NA not applicable, *m* meter, *rep* repetition, *s* second, *cm* centimeter

5 stretching exercises for the trunk and lower extremity, 3 strengthening exercises, 5 plyometric drills, and 3 soccer-specific agility activities (Table 17.5, see also Chap. 16).

Two studies have been published to date regarding the ability of this intervention to reduce the incidence of ACL injuries. In the first study, 1,885 trained high school female soccer players and 3,808 control players were followed over the course of 1 season [12]. A significant reduction was reported in the noncontact ACL injury incident rate between trained and control players (0.09 and 0.49 per 1,000 athlete-exposures, respectively, $P < .0001$). 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 of the PEP program entailed 583 female collegiate soccer athletes who participated in the intervention program and 852 players who served as controls [6]. The overall incidence of noncontact ACL ruptures per 1,000 athlete-exposures was 0.189 in untrained female athletes and 0.057 in trained female athletes ($P = .066$). The study lacked the statistical power to compare subgroups because of the smaller than expected number of noncontact ACL injuries reported (2 in the intervention and 10 in the control group). There was a significant reduction in the risk of all ACL injuries (contact and noncontact combined) in practice ($P = .01$) and during the second half of the season ($P = .02$). 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.

Pollard et al. [18] 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 1 season. Following training, a significant increase was noted in hip abduction (−4.9° vs. −7.7°, $P = .02$) and a significant decrease was found in hip internal rotation (7.1° vs. 1.9°, $P = .01$). There were no significant differences found in knee valgus or knee flexion angles.

Lim et al. [11] studied the effects of the PEP program on knee kinematic and kinetic variables in 11 high school female basketball players who trained during practice for 8 weeks. The program was slightly modified to include alternative exercise-warm down options and all training sessions were supervised by well-trained coaches. Significant improvements were found in isokinetic peak torques for hip abduction, hip extension, knee flexion, and the hamstrings-quadriceps ratio ($P < .05$). There was also a significant increase in knee flexion angle ($P = .02$) and knee separation distance ($P = .004$) 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.

Table 17.6 Knee ligament injury prevention (KLIP) program[a] [17]

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-legged jumps, single-legged lateral jumps, 45° lateral leaps
3	5, 6	Tuck jumps, single-legged lateral leaps, single-legged forward hops, combination jumps, 180° jumps, 45° lateral leaps
4	7 to end of season	Straight jumps, single-legged 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

Sigward et al. [19] measured the effects of the PEP program on knee valgus moments during a reactive side-step cutting task. Forty-eight female soccer players aged 9–17 years completed training 2×/week for 10 weeks. The authors reported a significant 14 % average decrease in the peak knee valgus moment, (0.49 vs. 0.56 Nm/kg·cm, $P = .02$) which was consistent across the age groups of prepubertal, pubertal, and postpubertal.

Vescovi et al. [23] trained 15 high school soccer players using the PEP program 3×/week for 12 weeks. These authors reported no significant improvements in vertical jump height, speed, or agility.

Knee Ligament Injury Prevention (KLIP) Program

Pfeiffer and associates [17] developed the knee ligament injury prevention (KLIP) program which was tested in high school female basketball, soccer, and volleyball athletes. The program was performed 2×/week for approximately 20 min throughout 1 season at either the beginning or end of practice (Table 17.6). There was no significant difference in the incidence of noncontact ACL injuries between 862 trained athletes and 577 control athletes (.17 and .08 per 1,000 athlete-exposures, 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. [9] 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 2×/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, $P = .0004$) and rate of force development (0.11 ± 0.03 and 0.08 ± 0.02 bw/ms, $P = .02$) on landing from a drop-jump. There was no significant increase in vertical jump height.

Pasanen Program

Pasanen et al. [15] developed an ACL intervention warm-up program for female floorball players (Table 17.7). Elite-level adult players in Finland trained 1–3×/week for 20–30 min during practice for 1 season. There was no significant difference in the incidence of ACL injuries between the 256 trained and 201 control players (.09 and .05 per 1,000 athlete-exposures, respectively). The study lacked the appropriate statistical power in regard to the number of noncontact ACL injuries (3 in each group). There was a significant reduction in noncontact leg injuries overall ($P < .001$) in the intervention group, with the greatest effects observed in ankle ligament injuries. The authors concluded that the training was effective and should be

Table 17.7 Pasanen program [15]

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 & 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-legged)	
Double-legged	2–3 × 10–15 reps
Single-legged	2–3 × 8–10 reps each leg
Balance exercise with medicine ball	
Single-legged	2–3 × 4–6 throws each leg
Balance board exercise (either double or single-legged)	
Double-legged: with or without stick or ball	2–3 × 20–30 s
Single-legged: with or without stick or ball	2–3 × 20–30 s each leg
Plyometrics (5–7 min)	
Forward jumps (double or single-legged)	
Double-leg jumps	2–3 × 3–5 reps
Single-legged 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-legged)	
Double-legged	
3 alternative exercises (backward & forward jumps, lateral jumps, or 3-dimensional jumps)	2–3 × 8–12 reps
Single-legged	
3 alternative exercises (backward & forward hops, lateral hops, or 3-dimenstional hops)	2–3 × 4–8 reps each leg
Strengthening (1 exercise for lower legs, 1 for core, 5–7 min)	
Double-legged squat with partner on back	2–3 × 8–12 reps
Single-legged split squat	2–3 × 4–8 reps each leg
Nordic hamstrings	2–3 × 4–8 reps
Isometric side & 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 & flexibility, 5 min)	
Seated hip & 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

included in the weekly training or teams and that training should begin no later than the age of 12 as greater improvements in motor technique and skills would be expected in younger athletes.

The "11" Program

Steffen et al. [22] developed an intervention warm-up program termed the "11" in female soccer players (Table 17.8). Participants in the

Table 17.8 The "11" program [22]

Exercises	Description	Duration
Core stability		
The bench	Leaning on elbows in the prone position, lift the upper body, hips, & 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 & hips until the shoulder, hip, & top leg are in straight line & parallel to the ground. Hold this position	15 s × 2 reps on each side
Balance		
Cross-country skiing	In single-legged stance, continuously bend & extend the knee of the supporting leg & swing the arms in rhythm	15 s × 2 reps on each leg
Chest pass in single-legged stance	Partner exercise with both players in single-legged stance. Throw a ball back & forth	15 s × 3 reps on each leg
Forward bend in single-legged stance	Same as above, but before throwing 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-legged stance	Same as above, but before throwing 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 & 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, & complete the zigzag course as fast as possible	2 reps each direction (20 m)
Bounding	Spring as high & far as possible off the supporting leg. Bring the knee of the trailing leg up as high as possible & the opposite arm in front of the body. Continuous bounding, switching legs on each take off	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

reps repetitions

under-17 league system in Norway were randomized to either the intervention group (1,073 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 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 2-jump tests.

The "11+" Program

In an effort to improve the results of the "11" training program, a modified intervention was developed and described by Soligard et al. (Table 17.9) [20]. A total of 125 soccer clubs in Norway participated for 1 season (8 months). There was no significant difference in the rate of

Table 17.9 The "11+" program [20]

Exercise	Duration
1. Running, 8 min (1 rep = 6–10 pairs parallel cones)	
Straight ahead	2 reps
Hip out	2 reps
Hip in	2 reps
Circling	2 reps
Running and jumping	2 reps
Running, quick run	2 reps
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-legged balance	
Level 1: holding ball	2 × 30 s (each leg)
Level 2: throwing 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-legged 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	
Running over pitch	2 reps
Bounding run	2 reps
Running and cutting	2 reps

reps repetitions, *s* seconds

acute noncontact injuries between the 1,055 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.

Warm-up for Injury Prevention and Performance (WIPP) Program

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 (see Chap. 14). WIPP incorporates the essential components of Sportsmetrics and a final agility component and is

Table 17.10 Warm-up for Injury Prevention and Performance (WIPP) program

Exercise	Duration
Dynamic warm-up:	
Straight leg march Hand walk Leg cradle walk Hip rotator walk	20 s each exercise
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-legged	30 s each leg
Lateral step, single-legged	20 s each leg
Supine hamstring, single-legged	30 s each leg
Abdominal crunch	60 s
Modified plank	60 s
Flexibility:	
Hamstring Hip flexor Quadriceps Gastrocnemius	20 s each side
Dynamic warm-up:	
Quick feet	30 s each direction
Nebraska drill	30 s each run

s seconds

20 min in duration (Table 17.10). The authors 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.

Grandstrand et al. [7] conducted a study in which a group of 12 soccer players aged 9–12 years underwent WIPP training 2×/week for 8 weeks. There was no statistically significant increase in knee separation distance on a drop-jump test or in vertical jump height. However, the authors noted that the knee separation distance values increased more than 25 % after training, which may be clinically significant. The authors also believed that the subjects were too young to accomplish the training and had to modify some of the exercises which were too difficult to perform correctly.

Kerlan-Jobe Orthopaedic 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 17.11). 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-legged hop test. After training, significant increases were noted in knee flexion angle at footstrike ($P = .003$) and maximum knee flexion angle during stance phase ($P = .006$). Significant decreases were noted for hip flexion at foot strike ($P = .05$), maximum hip external rotation ($P = .02$), maximum knee flexion moment ($P = .04$), and maximum dynamic knee valgus ($P = .04$). Vertical jump height increased ($P < .001$), and times for the single-legged hop improved for both legs ($P \leq .001$). 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.

DiStefano ACL Injury Prevention Programs

DiStefano and associates described 4 warm-up ACL injury prevention training programs: traditional, pediatric, general, and stratified [3–5]. However, 2 of these programs have only been studied in 9–10-year-old males and females, with no gender comparison, and are therefore not included in this chapter [4, 5].

The effects of the general and stratified ACL intervention training programs were studied 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-legged 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 (Table 17.12). All trainings were accomplished within 10–15 min at the start of every soccer practice 3–4×/week.

Changes in landing technique were assessed using the Landing Error Scoring System (LESS). The LESS rates 9 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 [14]. A total of 140 soccer players aged 11–17 years underwent training for 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.

Table 17.11 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-legged chest pass	20 each side
Single-legged forward-bend pass	20 each side
Single-legged figure of 8	20 each leg
Line jumps	20 reps
Lateral shuffle	20 each side
Bounding	20 reps

reps repetitions, *s* seconds

Table 17.12 DiStefano generalized and stratified injury prevention programs [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-legged 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-legged 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

[a]Subjects performed exercises according to performance on a double-legged squat test, classified as either medial knee displacement, toe out, or neutral
NA not applicable

Knee Injury Prevention Program (KIPP)

LaBella et al. [10] 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 1 athletic season (Table 17.13). Teams were cluster randomized by school to either the intervention or control group. A subset of 855 athletes reported information regarding age, playing experience, prior injuries, and race/ethnicity data.

After adjusting for these variables, the incidence rate for noncontact ACL injuries was significantly lower in the 485 trained athletes compared to the 370 control subjects (0.10 and 0.48 per 1,000 athlete-exposures, respectively, $P = .04$). 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.

Table 17.13 Knee Injury Prevention Program (KIPP) [10]

Exercise	Wk	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		
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
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	

Table 17.13 (continued)

Exercise	Wk	Duration
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-legged hop, hop, stick landing	Wk 2-on	5 reps each leg
Jump, jump, jump, vertical jump	Wk 2	NA
Single-legged 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	
Between 2 rows of 5 cones; rows 15-m apart		
Sprint to cone, backward jog to next cone		10 reps
Diagonal runs	All	
Between 2 rows of 5 cones; rows 15-m apart		
Sprint to cone, sprint to next cone		10 reps
Lateral shuffles	All	
Between 2 rows of 5 cones; rows 4.6-m apart		
Side shuffle from cone to cone		10 reps

Wk week, *reps* repetitions, *s* seconds, *NA* not applicable

Critical Points

- Eleven ACL intervention warm-up programs:
  - Myklebust
  - Petersen
  - Prevent Injury and Enhance Performance (PEP)
  - Knee ligament injury prevention (KLIP)
  - Pasanen
  - The “11”
  - The “11+”
  - Warm-up for Injury Prevention and Performance (WIPP) program
  - Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Training Program
  - DiStefano ACL injury prevention programs
  - Knee Injury Prevention Program (KIPP)

Outcomes of Programs

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. 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 was a trend for better results in terms of reduced ACL injury rates among teams or athletes who had high training attendance records compared to those who attended fewer sessions [13]. In addition, elite athletes may have had greater motivation to perform the training program due to problems with players sustaining ACL injuries in previous years [13]. In one investigation [13], elite players had more practices per week than lower level teams, which provided more opportunities to participate in the training program. 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.

Effect on ACL Injury Rate

Only two programs (PEP [12] and KIPP [10]) had a statistically significant effect in reducing the ACL injury incidence rate (Table 17.1). 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.

Effect on Athletic Performance Indices

There were ten studies that assessed the effect of an ACL intervention warm-up training program on athletic performance factors (Table 17.2). 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. The Myklebust [13] program increased 2-legged dynamic balance as measured by the KAT 2000 device. However, there were no significant improvements on a single-legged static balance test or on 3 single-legged functional hop tests. The Kerlan-Jobe [2] program increased vertical jump height a mean of 3.7 cm and improved times in a single-legged hop test by 0.14–0.17 s. Isokinetic hip and knee strength was enhanced in a modified PEP program [11]. However, no significant improvements were reported in lower extremity isokinetic strength in athletes who participated in the Myklebust or the “11” programs; in vertical jump height in the KLIP, WIPP, the “11”, or PEP programs; in speed or agility in the “11” or PEP programs; or in sports-specific tasks in the “11” program.

Effect on Neuromuscular Indices

Eight studies investigated the effect of ACL intervention warm-up training programs on neuromuscular indices. Changes in knee kinematics and kinetics on a drop-jump task were presented in five studies. Other tasks including a vertical jump, rebound jump, reactive side-step cut, 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, 9, 11, 19], while others had no such effect [7, 21]. Other programs had mixed results and their ability to improve neuromuscular indices remains unclear [2, 18].

Effect of Program Components

Most of the warm-up programs adopted a multifaceted approach in the selection of exercise components. Myklebust et al. [13] 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. [16] 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 (10 min) in order not to take time away from practice.

Pfeiffer et al. [17] 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. [22] 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 3-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 [12]. The authors acknowledged that the program may require repeated use over several weeks for athletes to demonstrate changes in strength, balance, and proprioception. To date, this program has only been shown to be effective in reducing the ACL injury rates in female soccer players.

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. The authors of this chapter 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.

References

1. Barber-Westin SD, Noyes FR, Smith ST et al (2009) Reducing the risk of noncontact anterior cruciate ligament injuries in the female athlete. Phys Sportsmed 37(3):49–61
2. Chappell JD, Limpisvasti O (2008) Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. Am J Sports Med 36(6): 1081–1086
3. DiStefano LJ, Padua DA, DiStefano MJ et al (2009) Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. Am J Sports Med 37(3):495–505
4. Distefano LJ, Padua DA, Blackburn JT et al (2010) Integrated injury prevention program improves balance and vertical jump height in children. J Strength Cond Res 24(2):332–342
5. DiStefano LJ, Blackburn JT, Marshall SW et al (2011) Effects of an age-specific anterior cruciate ligament injury prevention program on lower extremity biomechanics in children. Am J Sports Med 39(5): 949–957
6. Gilchrist J, Mandelbaum BR, Melancon H et al (2008) A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. Am J Sports Med 36(8):1476–1483
7. Grandstrand SL, Pfeiffer RP, Sabick MB et al (2006) The effects of a commercially available warm-up program on landing mechanics in female youth soccer players. J Strength Cond Res 20(2):331–335
8. Holm I, Fosdahl MA, Friis A et al (2004) Effect of neuromuscular training on proprioception, balance, muscle strength, and lower limb function in female team handball players. Clin J Sport Med 14(2): 88–94
9. Irmischer BS, Harris C, Pfeiffer RP et al (2004) Effects of a knee ligament injury prevention exercise program on impact forces in women. J Strength Cond Res 18(4):703–707
10. Labella CR, Huxford MR, Grissom J et al (2011) Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. Arch Pediatr Adolesc Med 165(11):1033–1040
11. Lim BO, Lee YS, Kim JG et al (2009) Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. Am J Sports Med 37(9):1728–1734
12. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010
13. Myklebust G, Engebretsen L, Braekken IH et al (2003) Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. Clin J Sport Med 13(2):71–78
14. Padua DA, Distefano LJ, Marshall SW et al (2012) Retention of movement pattern changes after a lower extremity injury prevention program is affected by program duration. Am J Sports Med 40(2):300–306
15. Pasanen K, Parkkari J, Pasanen M et al (2008) Neuromuscular training and the risk of leg injuries in female floorball players: cluster randomised controlled study. BMJ 337:a295
16. Petersen W, Braun C, Bock W et al (2005) A controlled prospective case control study of a prevention training program in female team handball players: the German experience. Arch Orthop Trauma Surg 125(9):614–621
17. Pfeiffer RP, Shea KG, Roberts D et al (2006) Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. J Bone Joint Surg Am 88(8):1769–1774
18. Pollard CD, Sigward SM, Ota S et al (2006) The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. Clin J Sport Med 16(3):223–227
19. Sigward S, Pollard CD, Powers CM (2008) Abstract #29. The influence of an acl injury prevention program on knee valgus moments during cutting: An evaluation of pre-pubertal, pubertal and post-pubertal female athletes. J Athl Train 43(5):559
20. Soligard T, Myklebust G, Steffen K et al (2008) Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. BMJ 337:a2469
21. Steffen K, Bakka HM, Myklebust G et al (2008) Performance aspects of an injury prevention program: a ten-week intervention in adolescent female football players. Scand J Med Sci Sports 18(5):596–604
22. Steffen K, Myklebust G, Olsen OE et al (2008) Preventing injuries in female youth football – a cluster-randomized controlled trial. Scand J Med Sci Sports 18(5):605–614
23. Vescovi JD, VanHeest JL (2010) Effects of an anterior cruciate ligament injury prevention program on performance in adolescent female soccer players. Scand J Med Sci Sports 20(3):394–402

Effect of Intervention Programs on Reducing the Incidence of ACL Injuries, Improving Neuromuscular Deficiencies, and Enhancing Athletic Performance

18

Sue D. Barber-Westin and Frank R. Noyes

Contents

S.D. Barber-Westin, B.S. (✉)
Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA
e-mail: sbwestin@csmref.org

F.R. Noyes, M.D.
Cincinnati Sportsmedicine and Orthopaedic Center, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Introduction

Since the first publications of knee ligament injury prevention training programs appeared in the sports medicine literature for skiing in 1995 [11] and female high school athletes in 1996 [19], at least 50 have followed that focused on female athletes (Table 18.1). Multiple investigations have been conducted to determine the effectiveness of these programs in reducing anterior cruciate ligament (ACL) injury rates [12, 20, 26, 30, 35, 42, 45, 46, 55], improving knee kinematic and kinetic factors [4, 6, 7, 9, 16, 17, 19, 21, 23, 28, 29, 32, 37–40, 61, 62, 64], and enhancing athletic performance indicators [2, 38–40, 54, 57, 58].

There exist many differences in opinion regarding the frequency, intensity, duration, and components that should comprise an ACL intervention training program. One issue is if a true reduction in the injury rate can be accomplished with so-called warm-up programs that are relatively short in session duration (10–20 min), but long in total training duration (for instance, 1 season). This is in contrast to preseason programs that lasts 6–8 weeks but require 60–120 min of training per session. A second issue is whether ACL intervention training should be modified

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_18, © Springer-Verlag Berlin Heidelberg 2012

Table 18.1 Summary of published ACL injury prevention programs for female athletes

Program [citation]	Program duration	Program components	ACL injury rate calculated by exposure data	Kinematic, kinetic data	Athletic performance test data
Sportsmetrics [20]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility (Chap. 14)	Yes	No	No
Myklebust [35]	15-min warm-up, 3×/wk for 5–7 wk, then 1×/wk in season	Floor, mat, wobble board (Table 17.3)	Yes	No	No
Petersen [45]	10-min warm-up, 3×/wk for 8 wk, then 1×/wk in season	Balance, plyometrics (Table 17.4)	Yes	No	No
PEP [30]	20-min warm-up in season	Running, flexibility, strength, plyometrics, agility (Table 17.5)	Yes	No	No
KLIP [46]	20-min warm-up, 2×/wk in season	Plyometrics, agility (Table 17.6)	Yes	No	No
The "11" [55]	15-min warm-up, 15 consecutive sessions, then 1×/wk in season	Core, balance, plyometrics, strength (Table 17.8)	Yes	No	No
PEP [12]	20-min warm-up in season	Running, flexibility, strength, plyometrics, agility (Table 17.5)	Yes	No	No
Pasanen [42]	20–30-min warm-up, 2–3×/wk in season	Running, balance, plyometrics, strength (Table 17.7)	Yes	No	No
KIPP [26]	20-min warm-up before practice in season	Plyometrics, strength, agility (Table 17.13)	Yes	No	No
Wojtys [62]	30 min, 3×/wk for 6 wk	3 programs: isokinetic, isotonic, agility	No	Yes	Yes
Sportsmetrics [19]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility (Chap. 14)	No	Yes	Yes
Sportsmetrics [61]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility (Chap. 14)	No	Yes	Yes
KLIP [23]	20-min warm-up, 2×/wk for 9 wk	Plyometrics, agility (Table 17.6)	No	Yes	Yes
Myklebust [21]	15-min warm-up, 1–3×/wk in season	Floor, mat, wobble board (Table 17.3)	No	Yes	Yes
Chimera [7]	20–30 min, 2×/wk for 6 wk off-season	Plyometrics	No	Yes	Yes
Sportsmetrics [37]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility (Chap. 14)	No	Yes	Yes
Myer [32]	90 min, 3×/wk for 6 wk	Plyometrics, strength, balance	No	Yes	Yes
Lephart [28]	30 min, 3×/wk for 8 wk	2 programs: plyometric (flexibility, balance, strength, agility), basic (flexibility, balance, strength)	No	Yes	Yes

Kerlan-Jobe [6]	10–15-min warm-up, 6×/wk for 6 wk in season or preseason	Strength, balance, plyometrics (Table 17.11)	No	Yes	Yes
Herman [16]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls	No	Yes	Yes
Oslo Sports Trauma Research Center [64]	20-min warm-up, 2×/wk for 18 wk in season	Balance, agility, plyometrics, strength	No	Yes	Yes
Herman [17]	45 min, 3×/wk for 9 wks	Strength training, resistance bands, exercise balls. Feedback in 1 group; 3 sessions, video landing technique analyzed	No	Yes	Yes
PEP, modified [29]	20-min warm-up in season	Running, flexibility, strength, plyometrics, agility, cooldown exercises added (Table 17.5).	No	Yes	Yes
DiStefano [9]	12–14-min warm-up, 3×/wk for 9 wk in season	2 programs: traditional (flexibility, balance, strength, agility, plyometrics), pediatric (dynamic flexibility, balance, plyometrics, strength)	No	Yes	Yes
Herrington [18]	15 min, 3×/wk for 4 wk	Plyometrics	No	Yes	Yes
Barendrecht [4]	15 min, 2×/wk for 10 wk in season	Agility, balance, plyometrics, strength; results from males and females combined	No	Yes	Yes
Sportsmetrics volleyball [38]	90–120 min, 3×/wk for 6 wk preseason	Volleyball-specific exercises added to Sportsmetrics program for agility, speed, endurance (Table 15.3)	No	Yes	Yes
Sportsmetrics Basketball [39]	90–120 min, 3×/wk for 6 wk preseason	Basketball-specific exercises added to Sportsmetrics program for agility, speed, endurance (Table 15.2)	No	Yes	Yes
Sportsmetrics soccer [40]	90–120 min, 3×/wk for 6 wk preseason	Soccer-specific exercises added to Sportsmetrics program for agility, speed, endurance (Table 15.1)	No	Yes	Yes
Paterno [43]	90 min, 3×/wk for 6 wk off-season	Balance, strength, plyometrics, resistance training	No	Yes	No
Myer [33]	90 min, 18 sessions over 7 wk	2 programs: plyometric, balance and dynamic stabilization	No	Yes	No
Hurd [22]	60 min, 10 sessions over 3–4 wk	Perturbation on balance board, strength, agility	No	Yes	No
PEP [47]	20-min warm-up, 2–3×/wk in season	Running, flexibility, strength, plyometrics, agility (Table 17.5)	No	Yes	No
WIPP [13]	20–25-min warm-up, 2×/wk for 9 wk in season	Plyometrics, strength, flexibility, agility (Table 17.10)	No	Yes	No
Myer [34]	60 min, 3×/wk for 7 wk	Training protocol not given	No	Yes	No
PEP [51]	20-min warm-up, 2×/wk for 10 wk in season	Running, flexibility, strength, plyometrics, agility (Table 17.5)	No	Yes	No

(continued)

Table 18.1 (continued)

Program [citation]	Program duration	Program components	ACL injury rate calculated by exposure data	Kinematic, kinetic data	Athletic performance test data
Kato [25]	20 min, 3×/wk for 4 wk during practice	Strength, plyometrics, balance	No	Yes	No
DiStefano [8]	10–15-min warm-up, 3–4×/wk in season	2 programs: 1 general, 1 designed on performance on squat test (Table 17.12)	No	Yes	No
McLeod [31]	90 min, 2×/wk for 6 wk in season	Strength, plyometrics, agility, balance	No	Yes	No
Wilderman [60]	15 min, 4×/wk for 6 wk in season	Agility drills	No	Yes	No
Sportsmetrics Volleyball [3]	90–120 min, 3×/wk for 6 wk preseason	Volleyball-specific exercises added to Sportsmetrics program for agility, speed, endurance (Table 15.3)	No	Yes	No
Nagano [36]	20 min, 3×/wk for 5 wk	Plyometrics, balance	No	Yes	No
The "11" [54]	15-min warm-up, 3×/wk for 10 wk in season	Core, balance, plyometrics, strength (Table 17.8)	No	No	Yes
Vescovi [57]	45–60 min, 3×/wk for 6 wk in season	Plyometric segment of Sportsmetrics	No	No	Yes
Sportsmetrics Tennis [2]	90 min, 3×/wk for 6 wk preseason	Tennis-specific exercises added to Sportsmetrics program for agility, speed, endurance (Table 15.4)	No	No	Yes
PEP [58]	20-min warm-up, 3×/wk for 12 wk in season	Running, flexibility, strength, plyometrics, agility (Table 17.5)	No	No	Yes
Tsang [56]	45–60 min, 3×/wk for 6 wk off-season	Plyometric segment of Sportsmetrics	No	No	Yes
Ettlinger [11]	Data collected over 3 seasons	Video awareness, cognitive training, workshops; results from males and females combined	No	No	No
Wedderkopp [59]	10–15 min in season	Balance board, 2 functional activities all major muscle groups	No	No	No
Frappier Acceleration [15]	3×/wk for 7 wks preseason	Plyometrics, cardiovascular conditioning, strength, sport cord, flexibility	No	No	No
Soderman [52]	10–15 min, 3×/wk in season	5 exercises on balance board	No	No	No
Oslo Sports Trauma Research Center Olsen [41]	15–20-min warm-up, 15 consecutive practices, then 1×/wk in season	Balance, running, strength, technique; results from males and females combined	No	No	No
The "11+" [53]	20-min warm-up, all practices in season	Running, strength, plyometrics, balance (Table 17.9)	No	No	No

PEP Prevent Injury and Enhance Performance Program, *KLIP* Knee Ligament Injury Prevention program, *WIPP* Warm-up for Injury Prevention and Performance program, *KIPP* Knee Injury Prevention Program, *wk* week, *min* minutes according to the athlete's age and sport. Can a program that is successful in adolescent soccer players have similar outcomes in adult handball players? Some investigators have proposed that training should be initiated in athletes who are as young as 12 years of age because modifications in body movement and awareness are easier to obtain in younger athletes than in adolescents or adults [41]. 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.

Two recent meta-analyses [50, 63] that assessed the ability of neuromuscular training programs to reduce ACL injury rates concluded that these intervention programs were indeed effective. Yoo et al. [63] found that the results were most pronounced in subjects <18 years old, in soccer players, and in programs that incorporated plyometric and strengthening components (rather than balancing). By pooling data from seven studies [15, 20, 30, 35, 45, 46, 52], the incidence of ACL injury was found to be 34 of 3,999 trained athletes and 123 of 6,462 controls. The odds ratio of the overall effects of training was 0.40 (95 % confidence intervals, 0.27–0.60) of all seven studies combined. The odds ratio of the four studies which focused only on noncontact ACL ruptures was 0.36 (95 % confidence intervals, 0.23–0.54). Sadoghi et al. [50] included nine studies [5, 12, 15, 20, 30, 44–46, 52] in their assessment and did not account for contact versus noncontact ACL ruptures. The pooled risk ratio for all studies was 0.38, indicating that athletes in the training programs had a 62 % reduction in the risk of ACL injury compared to controls. Female athletes had a risk reduction of 52 %, while male athletes had a reduction of 85 %. One problem is that these meta-analyses combined data from very different types of training programs and do not answer the three major issues discussed above.

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. This chapter serves to summarize the data, and the reader is referred to other chapters for further detail regarding these outcomes.

Critical Points

- More than 50 publications on ACL intervention programs 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

Reducing the Incidence of ACL Injuries

Nine studies to date have reported ACL injury rates in female athletes according to athlete exposures (Table 18.2) [12, 20, 26, 30, 35, 42, 45, 46, 55]. Five other studies that reported data on intervention programs did not provide ACL injury rates according to athlete exposures and are not included [11, 15, 52, 53, 59]. In addition, three injury intervention studies that focused only on male athletes are also not included in this review [1, 5, 24].

Three programs statistically reduced the ACL injury rate [20, 26, 30]. Sportsmetrics [20] was conducted in high school female soccer, basketball, and volleyball players before the start of the seasons (see Chap. 14). The results showed a

Table 18.2 Effect of intervention programs on ACL injury rates according to athlete exposures

Program [citation]	No. athletes[a]	No. athlete exposures		No. ACL injuries (per 1,000 athlete exposures)			Comments, study limitations
	Sports	Trained	Control	Trained	Control	P value	
Sportsmetrics [20]	366 trained, 463 control, 434 males Soccer, basketball, volleyball, high school	23,138	17,222 females, 21,390 males	0	5 (0.35) females, 1 (0.05) males	.05 for both control groups	Not randomized or double-blinded, higher number volleyball players in trained group, low number noncontact ACL injuries
Myklebust [35]	855 trained, season 1, 850 trained, season 2, 942 control Team handball, adult	172,692 186,805	208,936	23 (0.13) 17 (0.09)	29 (0.14)	NS	Not randomized, poor compliance with training, intervention training methods changed from 1st to 2nd season, unknown number contact vs. noncontact injuries
PEP [30]	1,885 trained, 3,818 control Soccer, high school	67,860	137,448	6 (0.09)	67 (0.49)	<.0001	Not randomized
Petersen [45]	134 trained, 142 control Team handball	NA	NA	1 (0.04)	5 (0.21)	NS	Not randomized, low number noncontact ACL injuries
KLIP [46]	189 trained, 244 control Soccer, high school	17,954	38,662	3 (0.167)	3 (0.078)	NS	Not randomized, low number noncontact ACL injuries
The "11" [55]	1,073 trained, 947 control Soccer, high school	66,423	65,725	4 (0.06)	5 (0.08)	.73	Poor compliance with training, low number noncontact ACL injuries
PEP [12]	583 trained, 852 control Soccer, college	35,220	52,919	2 (0.057)	10 (0.189)	.066	Low number noncontact ACL injuries
Pasanen [42]	256 trained, 201 control Floorball, adult	32,327	25,019	6 (0.18)	4 (0.16)	NS	Low number noncontact ACL injuries
KIPP [26]	485 trained, 370 control Soccer, basketball, high school	20,345	12,467	0.07	0.26	.04	Injuries not sorted according to sport, only 37 % of coaches invited participated

NA not available, *NS* not significant, *PEP* Prevent Injury and Enhance Performance Program, *KLIP* Knee Ligament Injury Prevention Program, *KIPP* Knee Injury Prevention Program

[a]Female athletes unless otherwise indicated

significant decrease ($P < .05$) in the rate of noncontact ACL injuries between the intervention group (366 athletes) and the female control group (463 athletes) and the male control group (434 athletes). The study had a low number of noncontact ACL ruptures and was not randomized. The Prevent Injury and Enhance Performance (PEP) warm-up program was conducted in high school female soccer players over the course of 1 season (see also Table 17.5) [30]. A significant reduction was reported in the noncontact ACL injury incident rate between the 1,885 trained and the 3,818 control players (0.09 and 0.49 per 1,000 athlete exposures, respectively, $P < .0001$). This study was also not randomized. The Knee Injury Prevention Program (KIPP) warm-up was conducted in high school female basketball and soccer players before practices over the course of 1 season (see also Table 17.13) [26]. A significant decrease was found in the noncontact injury incident rate between 485 trained and 370 control players (0.10 and 0.48 per 1,000 athlete exposures, respectively, $P = .04$).

Six studies [12, 35, 42, 45, 46, 55] failed to have an effect on reducing the ACL injury rate. Issues pertaining to poor compliance with training and a small number of 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. 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 athlete exposures, 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 [14, 49] have concluded that neuromuscular retraining can reduce the incidence of noncontact ACL injuries in female athletes. The International Olympic Committee Current Concepts Statement published in 2008 [49] 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.
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 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 alterations in neuromuscular indices that improve balance, strength, coordination, landing and cutting techniques, joint stabilization, and muscular preactivation and reactive patterns demonstrated in multiple studies to be discussed next.

Critical Points

- Nine studies reported ACL injury rates according to athlete exposures in female athletes.
  - Three significantly reduced injury rate: Sportsmetrics, PEP, and KIPP.
  - Six failed to reduce injury rate:
    - Poor compliance with training
    - Too few ACL injuries, limited statistical power
    - Lack of randomization
    - Changes intervention protocols over time

Changes in Knee and Hip Kinetics and Kinematics

Over 25 studies have been published to date which analyzed the effectiveness of knee injury prevention programs in changing kinematic or kinetic factors in female athletes [3, 4, 6, 8, 13, 16–19, 23, 25, 28, 29, 32–34, 36–40, 47, 51, 57, 60, 61, 64]. One important qualifier is that the majority of these investigations analyzed preplanned tasks measured in a controlled laboratory setting. The effectiveness of these types of programs in altering neuromuscular indices under reactive, unplanned, actual athletic conditions remains unknown.

Kinetics: Landing Forces

Statistically significant decreases in landing forces from a vertical jump [19] and step-land [23] and stop-jump tasks [17] have been reported following neuromuscular training (Table 18.3). One study [19] calculated a mean reduction of 456 N (103 lb, 46.72 kg) during a vertical jump following Sportsmetrics training in 11 female high school volleyball players (Fig. 18.1). Another study [17] reported a mean reduction of 22 % during a stop-jump task (Fig. 18.2) after training in recreational female athletes 18–30 years of age. Decreases in peak vertical impact forces of 26 % and rate of force development of 27 % were found in an investigation during a step-land task after completion of the KLIP training program in 14 active college students [23]. Barendrecht et al. [4] reported a 9 % increase in contact time on a drop-jump test in team handball players aged 13–19 years following training. These findings were interpreted as indicative of a softer landing technique.

In contrast, no reduction in landing forces was reported in several other investigations. These included tests involving a unilateral step-down or forward lunge [61], a vertical jump [28, 57], a drop-jump and vertical stop-jump [6], three stop-jump tasks [16], and a side-step pivot [60]. In five of these six studies, the populations under investigation were college or recreational athletes ≥18 years old. Factors believed to affect the ability of ACL intervention programs to alter landing forces include age (young vs. adult), athletic experience (competitive vs. recreational), type of instruction, and exercise protocol [57].

Kinetics: Moments

Statistically significant decreases in potentially deleterious moments have been noted by several investigations following ACL intervention training (Table 18.4) [6, 17, 19, 28, 32, 34, 51]. The first of such studies [19] reported decreases in knee abduction and adduction moments on a vertical jump after Sportsmetrics training. There were no changes in knee extension or flexion moments or in hip flexion-extension or adduction-abduction moments. Significant decreases in knee internal valgus (abduction) moments of 28 % and internal varus (adduction) moments of 38 % were reported following a similar training program on a drop-jump test [34]. Significant decreases in peak knee flexion moments and peak hip flexion moments were reported on a vertical jump test following a plyometric training program [28]. However, there were no effects on peak knee valgus moments or peak hip adduction moments.

A training program performed in collegiate soccer and basketball players produced mixed results in terms of reduction of potentially harmful moments [6]. 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. On a stop-jump test, significant training effects were reported only for knee valgus moments, with no improvements observed for knee external rotation or flexion or hip external rotation, abduction, or flexion moments.

One study reported a significant 13 % decrease in peak valgus moments during a side-step reactive cut test in 48 soccer players aged 9–17 years who underwent PEP training [51]. The effects occurred regardless of the stage of physical maturation. Significant reductions in knee valgus moments and hip adduction moments were reported on a stop-jump task following a combined strength-feedback program [17].

One study failed to find any improvements following strength training in knee extension or

Table 18.3 Effect ACL intervention training on landing forces

Program [citation]	Program duration	Program components	Subjects[a] Sports	Tests	Landing forces
Sportsmetrics [19]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility	11 trained females, 9 control males High school volleyball	Vertical jump	Decreased landing forces mean 456 N ($P = .006$)
KLIP [23]	20-min warm-up, 2×/wk in season	Plyometrics, agility	14 trained, 14 control College students	Step-land	Reduced peak vertical ground reaction forces 5.3 ± 1.0 to 3.9 ± 0.6 bw ($P = .0004$), rate force development 0.11 ± 0.03 to 0.08 ± 0.02 bw/meters per s ($P = .02$)
Herman [17]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls. Feedback in 1 group; 3 sessions, video landing technique analyzed	29 trained strength, feedback, 29 feedback only 18–30 y, recreational athletes	Stop-jump	All subjects combined decreased peak vertical ground reaction forces 1.61 ± 0.64 to $1.26 \pm 0.41 \times$ bw ($P < .001$)
Barendrecht [4]	15 min, 2×/wk for 10 wk in season	Agility, balance, plyometrics, strength	49 trained, 31 control Team handball males and females, 13–19 y	Drop-jump	Increased contact time 468 to 511 ms ($P = .001$)
Sportsmetrics [61]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility	11 trained, 8 control College basketball	Forward lunge, unilateral step-down	No improvement
Lephart [28]	30 min, 3×/wk for 8 wk	2 programs: plyometric, basic	27 trained High school athletes	Vertical jump	No improvement
Kerlan-Jobe [6]	10–15-min warm-up, 6×/wk for 6 wk in season or preseason	Strength, balance, plyometrics	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	No improvement
Herman [16]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls	33 trained, 33 control 18–30 y, recreational athletes	3 stop-jump tasks	No improvement
Vescovi [57]	45–60 min, 3×/wk for 6 wk in season	Plyometric segment of Sportsmetrics	10 trained, 10 control College intramural basketball	Vertical jump	No improvement
Wilderman [60]	15 min, 4×/wk for 6 wk in season	Agility drills	15 trained, 15 control College intramural basketball	Side-step pivot	No improvement

BW body weight, *MS* milliseconds, *KLIP* Knee Ligament Injury Prevention Program, *wk* week, *min* minutes, *y* years
[a]Female subjects unless otherwise indicated

Fig. 18.1 Vertical jump test on force plate

valgus moments or hip adduction or internal rotation moments during three stop-jump tasks [16]. Another investigation on a modified PEP program did not observe improvements in knee valgus moments on a rebound jump task [29].

Kinematics: Knee 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 18.5) [6, 8, 17, 28, 29, 32, 33, 36]. Slight average increases in knee flexion at foot strike of 5.2° [6] and 5.8° [33] 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 [36]. Improvements in maximum (peak) knee flexion during a drop-jump test [6, 32, 33], a rebound-jump task [29], and a single-leg drop landing have been observed [28, 36].

Seven 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 [4, 16, 19, 25, 47, 60, 64].

Kinematics: Hip Flexion Angles

Overall, eight studies to date have reported changes in hip angles following ACL intervention training (Table 18.5). Five of these [6, 17, 28, 33, 47] found statistically significant improvements in either flexion, abduction, adduction, external rotation, or internal rotation, while three others [16, 19, 64] failed to find improvements.

Increases in initial and peak hip flexion during a vertical jump were described in one study following plyometric training [28]. 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 [17]. Plyometric and balance training programs produced significant decreases in initial and maximum hip adduction angles on a drop-jump test [33]. However, these changes were not found on a medial drop-land test. 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 [47]. One study described significant decreases in hip flexion at foot strike and in maximal hip external rotation on a stop-jump task [6]. However, no significant differences were observed in hip kinematics on a drop-jump test.

Kinematics: Lower Limb Alignment

Several investigations have determined the effects of ACL intervention training on lower limb alignment

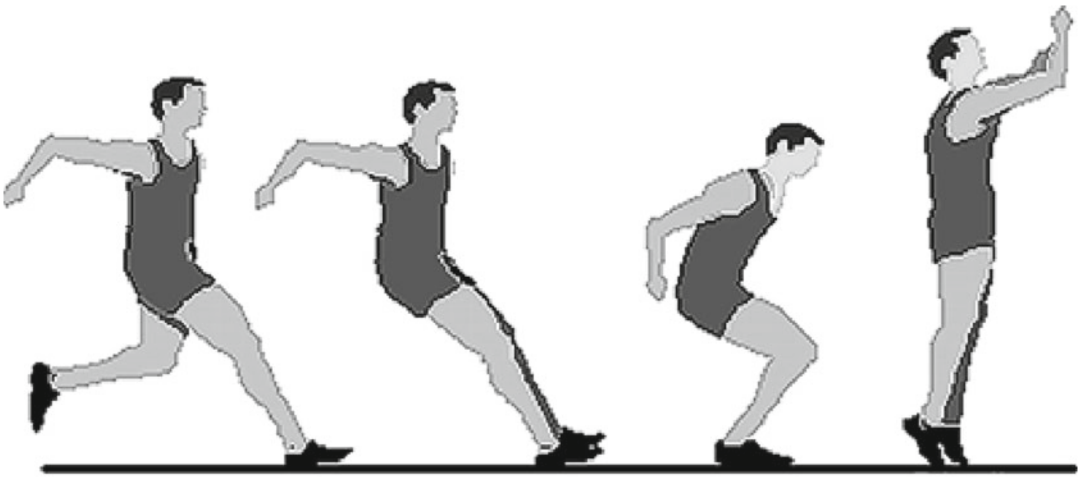


Fig. 18.2 Stop-jump task (Reprinted from Herman et al. [17]. With permission from SAGE Publications, Inc.)

during various jumping tasks (Table 18.6). 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. 18.3) or measuring varus-valgus angles in multiple planes.

Seven investigations reported statistically significant improvements in knee separation distance following training [3, 4, 29, 37–40]. High school female athletes improved a mean of 6.0 cm in one study [37], 4.8 cm in another study [38], 13.3 cm in a third study [39], and 8.5 cm in a fourth study [40] following Sportsmetrics training. Another group of high school female athletes improved a mean of 3.25 cm after completing the PEP program [29]. Overall lower limb alignment improved in approximately 70 % of female athletes following Sportsmetrics training and was retained 1 year later [3]. One study found no significant improvements in knee separation distances after completion of the Warm-up for Injury Prevention and Performance (WIPP) training program in a group of female athletes aged 9–11 years [13].

Only two investigations reported improvements in knee valgus angles following training [18, 25] while seven studies [6, 8, 16, 17, 28, 36, 47] found no training effects.

Critical Points

- Twenty-five studies assessed changes in kinematic or kinetic factors in females 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
– Knee flexion angles:
  - Increased in eight studies, but varied in amount of change and when improvements occurred during tasks
  - No change in seven studies
– Hip flexion angles:
  - Improved in five studies, no change in three studies
– Lower limb alignment:
  - Improved overall lower limb alignment in coronal plane in six studies on drop-jump
  - No change in knee valgus angles in seven studies

Table 18.4 Effect of ACL intervention training on moments

Program [citation]	Program duration	Program components	Subjects[a] Sports	Tests	Knee moments	Hip moments
Sportsmetrics [19]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility	11 trained, 9 control males High school athletes	Vertical jump	Decreased abduction 3.4 to 2.1 % bw × ht ($P<.05$), adduction 4.0 to 1.9 % bw × ht ($P<.05$) No improvement extension, flexion moments	No improvement abduction, adduction, or flexion-extension moments
Myer [32]	90 min, 3×/wk for 6 wk	Plyometrics, strength, balance	41 trained, 12 control High school athletes	Drop-jump	Decreased varus 34.0 ± 2.8 to 21.1 ± 1.7 Nm, valgus from 60.4 ± 5.5 to 43.4 ± 3.3 Nm right knee ($P<.001$) No effect varus or valgus moments left knee	NA
Lephart [28]	30 min, 3×/wk for 8 wk	2 programs: plyometric, basic	27 trained High school athletes	Vertical jump	Decreased peak flexion 0.076 ± 0.038 to 0.059 ± 0.01 Nm/bw × ht ($P=.01$) No effect peak valgus moment	Decreased flexion 0.170 ± 0.058 to 0.153 ± 0.033 Nm/bw × ht ($P=.008$) No effect peak adduction moment
Myer [34]	60 min, 3×/wk for 7 wk	Not given	18 trained Soccer, basketball, high school	Drop-jump	12 athletes with >25.25 Nm abduction moment significantly reduced ($P=.03$) 6 athletes with <25.25 Nm abduction moment did not improve	NA
Kerlan-Jobe [6]	10–15-min warm-up, 6×/wk for 6 wk in season or preseason	Strength, balance, plyometrics	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	Drop-jump: decreased maximum flexion 0.739 ± 0.37 to 0.583 ± 0.30 Nm ($P=.04$), external rotation −0.032 ± 0.12 to 0.027 ± 0.10 Nm ($P=.03$) No effect valgus moments Stop-jump: decreased valgus 0.863 ± 0.37 to 0.734 ± 0.31 Nm ($P=.04$) 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

PEP [51]	20-min warm-up in season	Running, flexibility, strength, plyometrics, agility	48 trained Soccer, 9–17 y	Side-step cut, reactive	Significant decrease peak valgus 0.56 to 0.49 Nm/kg·cm ($P = .02$) regardless of stage physical maturation	NA
Herman [17]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls. Feedback in 1 group; 3 sessions, video landing technique analyzed	29 trained strength and feedback, 29 feedback only 18–30 y, recreational athletes	Stop-jump	Decreased valgus 0.107 ± 0.060 to 0.064 ± 0.038 Nm/bw × ht ($P < .0001$) No improvement extension moment	Decreased adduction 0.115 ± 0.064 to 0.035 ± 0.130 Nm/bw × ht ($P < .0001$)
PEP, modified [29]	20-min warm-up in season	Running, flexibility, strength, plyometrics, agility, cooldown exercises added	11 trained, 11 control High school basketball	Rebound jump	No improvement valgus moment	NA
Herman [16]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls	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

BW body weight, *HT* height, *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program, *wk* week, *min* minutes, *y* years
[a]Female subjects unless otherwise indicated

Table 18.5 Effect of ACL intervention training on knee and hip flexion angles

Program [citation]	Program duration	Program components	Subjects[a] Sports	Tests	Knee flexion, abduction, rotation angles	Hip flexion, abduction, adduction, rotation angles
Myer [32]	90 min, 3×/wk for 6 wk	Plyometrics, strength, balance	41 trained, 12 control High school	Drop-jump	Increased total flexion-extension on landing 71.9 ± 1.4 to 76.9° ± 1.4° (right knee), 71.3 ± 1.5 to 77.3° ± 1.4° (left knee) (P < .001)	NA
Lephart [28]	30 min, 3×/wk for 8 wk	2 programs: plyometric, basic	27 trained High school	Vertical jump	Improved peak flexion 62.2 ± 9.7 to 86.0° ± 35.1° (plyometric group), 63.0 ± 18.1 to 70.9° ± 19.7° (basic training group) (P < .01), time to peak (P = .006) No effect flexion at initial contact	Improved flexion initial contact 1.9 ± 5.3 to 9.7° ± 8.7° (P = .02), peak 19.6 ± 9.3 to 27.2° ± 10.5° (P = 02) No effect initial contact or peak for abduction, adduction
PEP [47]	20-min warm-up in season	Running, flexibility, strength, plyometrics, agility	18 trained High school soccer	Drop-jump	No improvement peak flexion	Reduced peak internal rotation 7.1 to 1.9° (P = .01), increased abduction −4.9° to −7.7° (P = .02)
Myer [33]	90 min, 18 sessions over 7 wk	2 programs: polymeric, balance, dynamic stabilization	8 trained plyometric, 10 trained balance High school	Drop-jump, single-leg medial drop-land	Drop-jump: plyo group increased flexion initial contact 29.8 ± 6.6 to 35.6° ± 7.5°, peak 93.4 ± 54.2 to 101.6° ± 50.5° (P < .05) No effect abduction Medial drop: balance group increased peak flexion (P = .005). Both groups decreased abduction initial contact and peak (P = .04)	Drop-jump: both groups decreased adduction at initial contact −4.6° to −5.7°, peak −2.1° to −3.4° (P = .015) Medial drop: no effect adduction
Kerlan-Jobe [6]	10–15-min warm-up, 6×/wk for 6 wk in season or preseason	Strength, balance, plyometrics	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	Drop-jump: increased flexion foot strike 29.9 ± 9.0 to 35.1° ± 7.4° (P = .003), stance phase 81.3 ± 10.5 to 86.9° ± 10.3° (P = .006) Stop-jump: no effect flexion at foot strike or stance phase, no effect internal tibial rotation	Drop-jump: no effect flexion, abduction, external rotation at foot strike or peak Stop-jump: decreased flexion foot strike 72.2 ± 11.0 to 68.0° ± 8.9° (P = .05), peak external rotation 20.0 ± 12.5 to 13.1° ± 13.8° (P = .02) No effect abduction or internal rotation

PEP, modified [29]	20-min warm-up in season	Running, flexibility, strength, plyometrics, agility, cooldown exercises added	11 trained, 11 control High school basketball	Rebound jump	Increased peak flexion 92.66 ± 4.34 to 94.27° ± 3.44° (P = .02) No effect peak internal tibial rotation	NA
DiStefano [8]	10–15-min warm-up, 3–4×/wk in season	2 programs: 1 general, 1 designed on squat test performance	83 trained females, 90 trained males Soccer, 10–17 y	Drop-jump	Improved flexion foot strike (P = .009) (data not provided)	NA
Herman [17]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls Feedback in 1 group; 3 sessions, video landing technique analyzed	29 trained strength and feedback, 29 feedback only 18–30 y, recreational athletes	Stop-jump	All subjects combined increased peak flexion 27.20 ± 7.02 to 28.96° ± 5.23° (P = .05)	All subjects combined increased max flexion angle 44.77 ± 10.96 to 51.80° ± 8.91° (P < .001), abduction angle 8.88 ± 5.88 to 11.31° ± 8.72° (P = .03)
Nagano [36]	20 min, 3×/wk for 5 wk	Plyometrics, balance	8 trained College basketball	Single-leg drop landing	Significant increase flexion initial foot contact 19.3 ± 2.5 to 24.2° ± 2.1° (P < .01), peak 34.3 ± 2.5 to 40.2° ± 1.9° (P < .001) No effect external or internal tibial rotation	NA
Sportsmetrics [19]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility	11 trained females, 9 control males High school	Vertical jump	No improvement peak flexion	No improvement peak flexion
Herman [16]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls	33 trained, 33 control 18–30 y, recreational athletes	3 stop-jump tasks	No improvement peak flexion	No improvement peak flexion

(continued)

Table 18.5 (continued)

Program [citation]	Program duration	Program components	Subjects[a] Sports	Tests	Knee flexion, abduction, rotation angles	Hip flexion, abduction, adduction, rotation angles
Kato [25]	20 min, 3×/wk for 4 wk during practice	Strength, plyometrics, balance	10 trained, 10 control College basketball	Jump shot	No improvement peak flexion	NA
Oslo Sports Trauma Research Center [64]	20-min warm-up 2×/wk for 18 wk in season	Balance, agility, plyometrics, strength	20 trained Soccer, elite team handball, adults	Side cut	No improvement peak flexion	No improvement peak flexion
Wilderman [60]	15 min, 4×/wk for 6 wk in season	Agility drills	15 trained, 15 control College intramural basketball	Side-step pivot	No improvement flexion initial foot contact or peak	NA
Barendrecht [4]	15 min, 2×/wk for 10 wk in season	Agility, balance, plyometrics, strength	49 trained, 31 control Team handball males and females combined, 13–19 y	Drop-jump	No improvement peak flexion	NA

NA not assessed, *PEP* Prevent Injury and Enhance Performance Program, *wk* week, *min* minutes, *y* years
[a]Female subjects unless otherwise indicated

Table 18.6 Effect of ACL intervention training on lower limb alignment

Program [citation]	Program duration	Program components	Subjects[a] Sports	Tests	Lower limb alignment
Sportsmetrics [37]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility	62 trained, 325 untrained, 130 control males High school athletes	Drop-jump	Improved normalized knee separation distance 51 ± 19 to 68 % ± 18 %, absolute knee separation distance 23 ± 9 to 29 ± 8 cm ($P<.001$)
Kato [25]	20 min, 3×/wk for 4 wk during practice	Strength, plyometrics, balance	10 trained, 10 control College basketball	Jump shot	Improved peak lower extremity angle in coronal plane 36.9 ± 19.5 to 15.1° ± 6.5° ($P<.05$), torsion angle in horizontal plane 22.5 ± 12.8 to 17.1° ± 4.6° ($P<.05$)
PEP, modified [29]	20-min warm-up in season	Running, flexibility, strength, plyometrics, agility, cooldown exercises added	11 trained, 11 control High school basketball	Rebound jump	Improved knee separation distance 17.56 ± 2.92 to 20.81 ± 1.37 cm ($P=.004$)
Herrington [18]	15 min, 3×/wk for 4 wk	Plyometrics	15 trained Elite basketball, 18–22 y	Drop-jump, jump shot	Drop-jump: decreased knee valgus angle 9.8° left leg ($P=.002$), 12.3° right leg ($P=.0001$) Jump shot: decreased knee valgus angle 4.5° left leg ($P=.03$), 4.3° right leg ($P=.01$)
Sportsmetrics [3]	90–120 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility	16 trained High school volleyball	Drop-jump	Improved normalized knee separation distance immediately after training 50 ± 16 to 67 % ± 17 % ($P<.01$) and 1 yr later 74 % ± 17 % ($P<.001$)
Barendrecht [4]	15 min, 2×/wk for 10 wk in season	Agility, balance, plyometrics, strength	49 trained, 31 control Team handball males and females combined, 13–19 y	Drop-jump	Improved absolute knee separation distance 14.71 to 16.94 cm ($P<.001$), normalized knee separation distance 51.92 to 56.20 % ($P=.005$). Subjects classified as "above average valgus" (<46.96 % normalized knee separation distance) pretrain had greater improvements than those classified as "below average valgus"
Sportsmetrics Volleyball [38]	90–120 min, 3×/wk for 6 wk preseason	Volleyball-specific exercises added to Sportsmetrics program for agility, speed, endurance	34 trained High school volleyball	Drop-jump	Improved absolute knee separation distance 21.1 ± 8.2 to 25.9 ± 5.2 cm ($P=.002$), normalized knee separation distance 56.3 ± 19.1 to 63.3 % ± 12.7 % ($P=.04$)
Sportsmetrics Basketball [39]	90–120 min, 3×/wk for 6 wk preseason	Basketball-specific exercises added to Sportsmetrics program for agility, speed, endurance	57 trained High school basketball	Drop-jump	Improved absolute knee separation distance 18.5 ± 7.4 to 31.8 ± 10.36 cm ($P<.0001$), normalized knee separation distance 44.9 ± 17.2 to 74.2 % ± 18.8 % ($P<.0001$)
Sportsmetrics Soccer [40]	90–120 min, 3×/wk for 6 wk preseason	Soccer-specific exercises added to Sportsmetrics program for agility, speed, endurance	62 trained High school soccer	Drop-jump	Improved absolute knee separation distance 14.6 ± 3.6 to 23.1 ± 6.4 cm ($P<.0001$), normalized knee separation distance 35.9 ± 7.4 to 54.2 % ± 13.7 % ($P<.0001$)

(continued)

Table 18.6 (continued)

Program [citation]	Program duration	Program components	Subjects[a] Sports	Tests	Lower limb alignment
Lephart [28]	30 min, 3×/wk for 8 wk	2 programs: plyometric, basic	27 trained High school athletes	Vertical jump	No improvement knee valgus angle at foot strike or peak
PEP [47]	20-min warm-up in season	Running, flexibility, strength, plyometrics, agility	18 trained High school soccer	Drop-jump	No improvement peak knee valgus angle
WIPP [13]	20–25-min warm-up, 2×/wk for 9 wk in season	Plyometrics, strength, flexibility, agility	12 trained, 9 control Soccer, 9–11 y	Drop-jump	No improvement absolute or normalized knee separation distances
Kerlan-Jobe [6]	10–15-min warm-up, 6×/wk for 6 wk in season or preseason	Strength, balance, plyometrics	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	Drop-jump: no improvement knee valgus angle at foot strike or peak Stop-jump: no improvement knee valgus angle at foot strike or peak
Herman [16]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls	33 trained, 33 control Recreational athletes, 18–30 y	3 stop-jump tasks	No improvement peak knee valgus angle
DiStefano [8]	10–15-min warm-up, 3–4×/wk in season	2 programs: 1 general, 1 designed on performance on squat test	83 trained females, 90 trained males Soccer, 10–17 y	Drop-jump	No improvement knee valgus
Herman [17]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls. Feedback in 1 group; 3 sessions, video landing technique analyzed	29 trained-strength and feedback, 29 feedback only Recreational athletes, 18–30 y	Stop-jump	No improvement peak knee valgus angle
Nagano [36]	20 min, 3×/wk for 5 wk	Plyometrics, balance	8 trained College basketball	Single-leg drop landing	No change valgus angle at foot strike or peak

PEP Prevent Injury and Enhance Performance Program, *wk* week, *min* minutes, *y* years
[a]Female subjects unless otherwise indicated

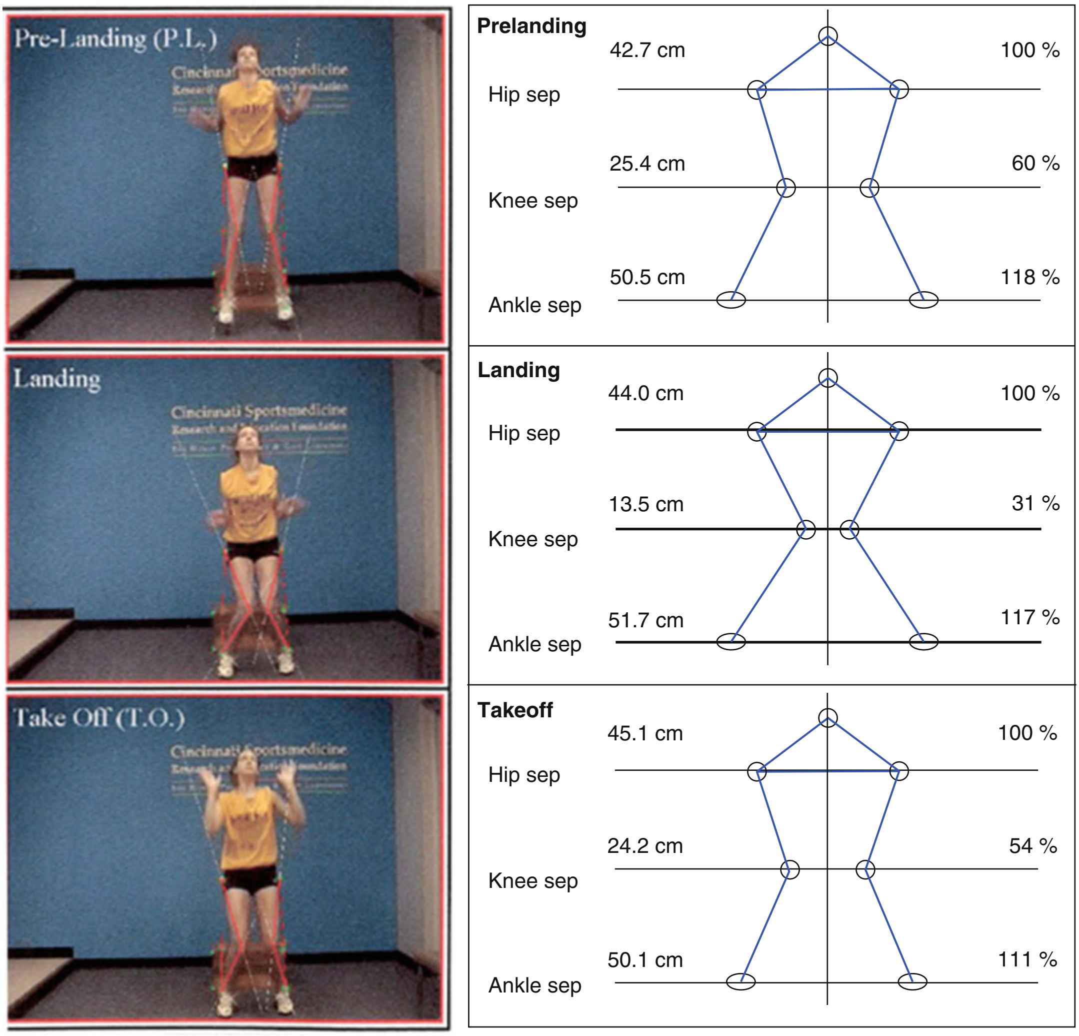


Fig. 18.3 Drop-jump video test. Three photographs are produced from the prelanding, landing, and takeoff phases. The centimeters of distance between the hips, knees, and ankles are calculated along with normalized knee and ankle separation distances (according to the hip separation distance) using commercially 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

Alterations in Lower Extremity Strength and Muscle Activation Patterns

A frequent finding among studies is a statistically significant increase in lower extremity isokinetic (Fig. 18.4) and isometric strength (Table 18.7). Improvements in the strength of the hamstrings [16, 17, 19, 29, 37, 56, 60, 61], quadriceps [16, 17, 28, 62], gluteus maximum and medius [16, 17], hip abduction [29], and in the hamstring/quadriceps ratio [19, 29, 37, 56, 61] have been reported after 6–9 weeks of training. In addition, several studies [22, 28, 36, 60, 62, 64] reported changes in electromyographic (EMG) muscle activation patterns after ACL intervention training that appear to demonstrate an earlier onset of hamstring activity, along with a reduction in quadriceps activity, during drop-jump, vertical

Fig. 18.4 Isokinetic knee flexion-extension strength test on Biodex isokinetic dynamometer (Biodex Corporation, Shirley, NY)

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: eight studies
  - Quadriceps: four studies
  - Hamstring-quadriceps ratio: five studies
- Muscle activation patterns:
  - Alterations in six studies: earlier onset hamstring activity, reduced quadriceps activity

Effect on Balance and Proprioception

Few studies to date have assessed the effectiveness of ACL intervention training programs on balance and proprioception (Table 18.8). One investigation [21] in elite adult team handball players found statistically significant improvements on a 2-legged balance test on the KAT 2000 (OEM Medical, Carlsbad, CA), but no improvement on a single-legged balance test. There was also no improvement in proprioception in regard to threshold to detect passive motion. A study [43] involving high school athletes reported improvements in single-leg total stability and anterior-posterior stability on the Biodex Stability System (Biodex Corporation, Shirley, NY, Fig. 18.5) after training. There was no improvement in medial-lateral stability in these subjects. Another investigation [31] involving high school athletes 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 to 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. A group of athletes 9–10 years of age

Table 18.7 Effect of ACL intervention training on lower extremity strength, muscle activation patterns

Program [citation]	Subjects[a] Sports	Tests	Isokinetic strength	Isometric strength	EMG analyses
Wojtys [62]	16 trained, 16 trained males Mean age, 25.4 y	Isokinetic quadriceps, hamstring peak torque, time to peak torque 60°/s, 240°/s; ankle planter flexion 180°/s	Improved quadriceps and plantar flexion peak torques isokinetic trained group ($P < .01$)	NA	Agility-trained group improved response times in medial hamstring, gastrocnemius, quadriceps muscles
		Anterior tibial translation stress test: EMG	No improvement agility or isotonic trained groups		No improvement isokinetic or isotonic trained groups
Sportsmetrics [19]	11 trained, 9 control males High school athletes	Isokinetic quadriceps, hamstring peak torque, avg power 60°/s, 360°/s	Increased hamstring peak torque ($P = .01$), mean power ($P < .05$), hamstring/quadriceps ratio ($P < .05$)	NA	NA
Sportsmetrics [61]	11 trained, 8 control College basketball	Isokinetic quadriceps, hamstring strength 60°/s, 300°/s	Improved hamstring peak torque ($P = .008$) and hamstring-quadriceps ratio ($P = .04$) 60°/s. No effect hamstring peak torque or hamstring-quadriceps ratio 300°/s. No effect quadriceps peak torque.	NA	NA
Sportsmetrics [37]	62 trained, 325 untrained, 130 control males High school athletes	Isokinetic quadriceps, hamstring peak torque 300°/s	Increased hamstring peak torque both legs ($P < .0001$) and hamstring/quadriceps ratio nondominant leg ($P = .001$)	NA	NA
Lephart [28]	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 ($P < .01$). No effect hamstring peak torque	No improvement hip abduction peak torque	Earlier onset gluteus medius in plyometric group vs. strength group ($P < .05$), both groups greater gluteus medius preactivity ($P < .05$) Plyometric group reduced time to peak medial hamstring reactivity after foot strike ($P < .05$) No change vastus lateralis, lateral hamstring peak EMG preactivity or reactivity phases.

(continued)

Table 18.7 (continued)

Program [citation]	Subjects[a] Sports	Tests	Isokinetic strength	Isometric strength	EMG analyses
Herman [16]	33 trained, 33 control 18–30 y, recreational athletes	Max voluntary isometric contraction	NA	Improved quadriceps, hamstrings, gluteus maximus, gluteus medius ($P<.001$).	NA
Herman [17]	29 trained strength and feedback (ST-FB), 29 feedback only 18–30 y, recreational athletes	Max voluntary isometric contraction	NA	Strength gains in ST-FB group for quadriceps, hamstrings, gluteus maximus, gluteus medius ($P<.001$)	NA
PEP, modified [29]	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 ($P=.004$ to .04) and hamstring-quadriceps ratio. Decreased quadriceps torque ($P=.04$)	NA	NA
Wilderman [60]	15 trained, 15 control College intramural basketball	Max voluntary isometric contraction, side-step pivot	NA	Increased medial hamstrings ($P<.001$)	Increased medial hamstring activation during loading phase ($P<.001$), decreased vastus medialis oblique activation. No effect lateral hamstring activation
Tsang [56]	11 trained, 14 control College students	Isokinetic quadriceps, hamstrings 60°/s, 120°/s	At 120°/s, improved hamstring power 30.76 ± 7.69 to 35.56 ± 7.92 ($P=.02$), peak torque 24.71 ± 4.85 to 27.20 ± 5.16 ($P=.03$), hamstring-quadriceps ratio 53.21 to 56.72 (P not given) No effect hamstring power or peak torque 60°/s, quadriceps power or peak torque 60°/s or 120°/s	NA	NA
Chimera [7]	9 trained, 9 control College soccer, field hockey	Drop-jump EMG analysis preparatory, reactive phases	NA	NA	Increased hip adductor activity ($P<.05$), adductor-to-abductor muscle coactivation ($P=.04$) during preparatory phase. Improved quadriceps-to-hamstring muscle coactivation ($P=.053$) reactive phase

Hurd [22]	10 trained, 10 control males College athletes	Gait analysis, normal speed walk on perturbation platform	NA	NA	Before training, female peak hamstring activity occurred after heel strike. After training, females had earlier onset time to peak hamstring activity (before heel strike), higher hamstring activity, and reduced vastus lateralis activity
Oslo Sports Trauma Research Center [64]	20 trained Soccer, elite team handball, adults	Side cut, EMG analysis	NA	NA	Greater semitendinosus muscle activity preland ($P<.01$) and land ($P<.05$) phases. Reduced activity gluteus medius preland ($P<.05$) and land ($P<.05$) phases. Reduced activity biceps femoris landing phase ($P<.01$). Reduced time to onset semitendinosus activity during preland phase ($P<.05$).
Nagano [36]	8 trained Collegiate basketball	Single-leg drop landing, max voluntary isometric contraction	NA	NA	Increased hamstring activity before foot strike ($P<.05$). No effect hamstring activity after foot strike. No differences rectus femoris activity, hamstring-quadriceps ratio before or after foot strike
Myklebust [21]	27 trained Elite team handball, adult	Isokinetic quadriceps, hamstrings 60°/s, 240°/s	No improvement quadriceps, hamstrings, or hamstring-quadriceps ratio	NA	NA
The "11" [54]	17 trained, 14 control Soccer, 16–18 y	Isokinetic quadriceps, hamstring peak torque 60°/s and 240°/s, isometric hip test	No improvement	No improvement hip abductors, adductors	NA

NA not assessed, *PEP* Prevent Injury and Enhance Performance Program, *wk* week, *min* minutes, *y* years
[a]Female subjects unless otherwise indicated

Table 18.8 Effect of ACL intervention training on balance and proprioception

Program [citation]	Program duration	Program components	Subjects[a] Sports	Tests	Results
Myklebust [21]	15-min warm-up, 1–3×/wk in season	Floor, mat, wobble board	27 trained	Balance: KAT 2000 balance index score 1-leg, 2-legs	2-legs: improved 924.1 ± 225.5 to 778.9 ± 174.4 (P = .003)
			Elite team handball, adult	Proprioception: threshold to detect passive motion	1-leg: no improvement Proprioception: no improvement
Paterno [43]	90 min, 3×/wk for 6 wk off-season	Balance, strength, plyometrics, resistance training	41 trained	Biodex stability system: total stability index, AP stability index, ML stability index, 1-leg	Total stability: improved 4.1 ± 1.6 to 3.3 ± 1.1 right leg, 4.4 ± 2.6 to 3.6 ± 1.3 left leg (P = .004)
			High school athletes		AP stability: improved 3.6 ± 1.6 to 2.7 ± 1.0 right leg, 3.9 ± 2.3 to 3.0 ± 1.2 left leg (P = .001) ML stability: no improvement
McLeod [31]	90 min, 2×/wk for 6 wk in season	Strength, plyometrics, agility, balance	27 trained, 23 control	Balance Error Scoring System (BESS): 6 20-s balance tests in different stances and on different surfaces, static balance	BESS: trained group fewer errors than pretrain and control group (P = .03)
			High school athletes	Star Excursion Balance Test (SEBT): distance reached in anteromedial, medial, posterior, and lateral directions, dynamic balance	SEBT: improved all directions (P < .001)
DiStefano [9]	12–14-min warm-up, 3×/wk for 9 wk in season	2 programs: traditional (flexibility, balance, strength, agility, plyometrics), pediatric (dynamic flexibility, balance, plyometrics, strength)	19 trained pediatric program, 22 trained traditional program, 25 control males and females 9–10 y	Time to stabilization, dynamic balance AP, and ML, single-leg drop-jump, dominant leg	Improved AP in traditional program only; mean − 0.92 ± 0.49 s (P < .05) No improvement ML either program

AP anterior-posterior, *ML* medial-lateral, *wk* week, *min* minutes, *y* years
[a]Female subjects unless otherwise indicated

Fig. 18.5 Single-leg balance test on Biodex Stability System (Biodex Corporation, Shirley, NY)

showed improvements after completing a traditional adult training program in time to stabilization from a single-leg drop-jump test in the anterior-posterior direction [9]. There was no improvement in the medial-lateral direction nor were there any improvements in this test in a group of athletes who completed a pediatric training program.

Critical Points
- Few studies to date
- Improvements in single-leg balance reported

Effect of Age, Gender, and ACL Training Program on Landing Technique

DiStefano and associates [8] assessed the effects of age in two groups (10–13 years, 14–17 years), gender, baseline landing technique (excellent, good, moderate, poor), and ACL intervention training programs (generalized, stratified) on landing patterns during a drop-jump task in 173 subjects. The Landing Error Scoring System (LESS) was used to measure landing patterns. This system rates nine jump-land characteristics, with a higher score indicating a greater number of landing errors and a poor technique. Subjects who were randomly assigned to the stratified intervention program underwent a double-legged squat test at baseline to determine the specific training exercises to be completed. Subjects with the poorest baseline LESS scores demonstrated the greatest improvements in landing technique ($P < .0001$). There were no differences between genders or the programs, but subjects 14–17 years old improved their landing technique more than those who were 10–13 years old ($P < .05$). The study questioned the applicability of current ACL intervention training techniques in younger athletes and failed to prove that a program stratified according to baseline landing patterns was more effective than a general program followed by all athletes.

Critical Points

- Few studies to date
- Subjects with poor Landing Error Scoring System greatest improvements after training in landing technique:
  - No differences between males and females
  - Subjects 14–17 years old improved more than those 10–13 years old

Enhancing Athletic Performance

There have been multiple studies which documented changes in athletic performance indicators following ACL injury prevention training in female athletes (Table 18.9) [2, 4, 6, 7, 9, 13, 18, 19, 21, 23, 29, 32, 38–40, 54, 57, 58, 64]. Vertical jump height is one of the most common indices tested, with mixed results reported. Statistically significant improvements have been noted in seven studies, with mean published post-train increases ranging from 1.2 to 3.8 cm [6, 9, 19, 32, 38, 39, 64]. Seven other studies [13, 23, 29, 40, 54, 57, 58] found no increases in jump height after training.

Statistically significant increases in the distance hopped during various single-leg hop tests have been reported after training [2, 4, 18, 32]. One study [32] reported mean increases in a single hop test in the right and left legs of 10.4 and 8.5 cm, respectively ($P < .001$), while another investigation [4] observed mean increases of 4.1 and 6.2 cm in the dominant and nondominant legs, respectively ($P < .01$). Mean increases in a triple crossover hop test of 36.3 and 36.1 cm in the right and left legs, respectively ($P \leq .05$), were found in youth tennis players following training [2]. Elite basketball players aged 18–22 years improved the distance on this test in a separate study by 110–111 cm ($P = .001$) [18]. Another study [6] assessed a timed single-leg hop over 6.1 m. Significant improvements were found after training for the right and left leg of 0.14 and 0.17 s, respectively ($P < .001$).

Sprint times have been assessed in several investigations before and after training, with conflicting results reported. One study [32] reported improvements in a 9.1-m run from 1.80 ± 0.02 to 1.73 ± 0.01 s ($P < .001$). Another investigation observed improvement in 1-court and 2-court suicide times in tennis players [2]. Improvement in the mean agility *t*-test time was reported in a study in high school soccer players [40]. However, four studies reported no improvements in sprint speed after training [7, 39, 54, 58].

Estimated VO_2max has been measured in three investigations using the multistage fitness test [38–40]. One study [38] 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 ($P < .001$). A second study [39] of female high school basketball players reported a mean improvement from 34.6 ± 4.5

Table 18.9 Effect of ACL intervention training on athletic performance

Program [citation]	Subjects[a] Sports	Tests	Vertical jump	Single-leg hop tests	Sprint speed, agility	VO_2max, core strength
Sportsmetrics [19]	11 trained females, 9 control males High school athletes	Vertical jump	Increased 3.8 ± 1.3 cm ($P = .016$)	NA	NA	NA
KLIP [23]	14 trained, 14 control College students	Vertical jump	No improvement	NA	NA	NA
Myklebust [21]	27 trained Elite team handball adult	Single-leg hop, triple jump, stair hop	NA	No improvement	NA	NA
Chimera [7]	9 trained, 9 control College soccer, field hockey	Vertical jump, 36.57-m sprint	Improved 5.8 % (mean 2.54 ± 2.97 cm, $P = .009$), but not significantly different from control group	NA	Improved, but not significantly different from control group	NA
Myer [32]	41 trained, 12 control High school athletes	Vertical jump, sprint 9.1-m, single-leg hop	Increased mean 3.3 cm, 39.9 ± 0.9 to 43.2 ± 1.1 cm ($P < .001$)	Increased 165.1 ± 3.0 to 175.5 ± 2.6 cm right leg, 165.1 ± 2.7 to 173.6 ± 2.5 cm left leg ($P < .001$)	Improved 1.80 ± 0.02 to 1.73 ± 0.01 s ($P < .001$)	NA
WIPP [13]	12 trained, 9 control Soccer, 9–11 y	Drop-jump	No improvement	NA	NA	NA
Oslo Sports Trauma Research Center [64]	20 trained, 8 untrained Elite handball, soccer adult	Vertical jump	Increased 27 ± 4 to 29 ± 4 cm ($P < .001$)	NA	NA	NA
The "11" [54]	17 trained, 14 control Soccer players, 16–18 y	Vertical jump, sprint running, soccer skill tests	No improvement	NA	No improvements	NA
Kerlan-Jobe [6]	30 trained College soccer, basketball	Vertical jump, timed single-leg hop	Increased mean 3.7 cm, 45.1 ± 14.1 to 48.8 ± 13.9 cm ($P < .001$)	Improved 2.17 ± 0.4 to 2.03 ± 0.3 s right leg, 2.17 ± 0.4 to 2.0 ± 0.2 s left leg ($P < .001$)	NA	NA
Vescovi [57]	10 trained, 10 control College intramural basketball	Vertical jump	No improvement	NA	NA	NA

(continued)

Table 18.9 (continued)

Program [citation]	Subjects[a] Sports	Tests	Vertical jump	Single-leg hop tests	Sprint speed, agility	VO_2max, core strength
PEP, modified [29]	11 trained, 11 control High school basketball	Rebound jump	No improvement	NA	NA	NA
DiStefano [9]	19 trained pediatric program, 22 trained traditional program, 25 control males and females 9–10 y	Vertical jump	Increased mean 1.70 ± 2.80 cm (P < .05) in traditional trained group only	NA	NA	NA
PEP [58]	15 trained, 16 control Soccer, adolescents	Countermovement vertical jump, 9.1, 18.3, 27.4, 36.6-m sprints, Illinois agility, pro-agility	No improvement	NA	No improvement	NA
Herrington [18]	15 trained Elite basketball, 18–22 y	Single-leg triple crossover hop test	NA	Increased mean 111 cm left leg, 110 cm right leg (P = .001)	NA	NA
Sportsmetrics Tennis [2]	10 trained females, 5 trained males 11–16 y	Single-leg hop, single-leg triple crossover hop, 1- and 2-court suicides, tennis skill tests, abdominal endurance	NA	Increased crossover triple hop 330.4 ± 71.7 to 366.7 ± 59.8 cm (P = .05) right leg, 325.7 ± 81.6 to 361.8 ± 66.2 cm (P = .03) left leg No improvement single hop	Improved 1-court suicide 20.02 ± 1.48 to 16.30 ± 1.14 s (P < .0001), 2-court suicide 100.03 ± 15.31 to 90.35 ± 10.05 s (P = .02), all tennis skill tests (P = .0008 to .003)	Improved abdominal endurance 92.3 ± 59.0 to 145.2 ± 62.1 s (P = .01)
Sportsmetrics Volleyball [38]	34 trained Volleyball, high school	Vertical jump, multistage fitness test, sit-up test	Increased mean 1.2 cm, 40.1 ± 7.1 to 41.5 ± 4.5 cm (P = .03)	NA	NA	Improved estimated VO_2max 39.4 ± 4.8 to 41.4 ± 4.0 ml/kg/min (P < .001). Increased sit-up 37.7 ± 5.3 to 40.5 ± 5.9 reps (P = .03)

Sportsmetrics Basketball [39]	57 trained Basketball, high school	Vertical jump, multistage fitness test, 18.29-m sprint	Increased mean 2.3 cm, 26.2 ± 12.3 to 28.5 ± 12 cm ($P < .0001$)	NA	No improvement	Improved estimated VO_2max 34.6 ± 4.5 to 39.5 ± 5.7 ml/kg/min ($P < .0001$)
Sportsmetrics Soccer [40]	62 trained Soccer, High school	Vertical jump, *t*-test, 37-m sprint, multistage fitness test	Increased mean 1.3 cm, 40.7 ± 8.9 to 42.1 ± 8.3 cm ($P = .04$); however, effect size small (.08)	NA	Improved *t*-test from 12.05 ± 0.87 to 11.31 ± 0.69 s ($P < .0001$)	Improved estimated VO_2max 37.9 ± 4.5 to 40.1 ± 4.7 ml/kg/min ($P < .0001$)
Barendrecht [4]	49 trained, 31 control Team handball males and females combined, 13–19 y	Single-leg hop for distance	NA	Increased 179.4 to 183.5 cm dominant leg ($P = .005$), 178.7 to 184.9 cm nondominant ($P < .001$) leg	NA	NA

NA not assessed, *KLIP* Knee Ligament Injury Prevention Program, *WIPP* Warm-up for Injury Prevention and Performance program, *PEP* Prevent Injury and Enhance Performance Program, *y* years

[a]Female subjects unless otherwise indicated

to 39.5 ± 5.7 ml/kg/min ($P < .0001$). A third investigation [40] of female high school soccer players found a mean improvement from 37.9 ± 4.5 to 410.1 ± 4.7 ml/kg/min ($P < .0001$).

Improvements in abdominal strength and endurance have been documented after training in two studies. High school volleyball players improved in the 60-s sit-up test, with a mean of 2.7 ± 4.8 more reps following training [38]. Junior tennis players improved a mean of 52.9 ± 59.3 s in an abdominal endurance test [2].

ACL Intervention Training in Prepubescent Athletes

To date, the majority of investigations of ACL intervention programs have focused on high school, collegiate, or adult athletes. The ability of these programs to influence neuromuscular and performance indices in younger, prepubescent athletes remains unclear. Grandstrand et al. [13] assessed the effectiveness of the WIPP program on landing mechanics during a drop-jump in a group of 12 female soccer players 9–11 years old. There were no significant improvements in absolute or normalized knee separation distances or vertical jump height following 8 weeks of training. However, knee separation values increased more than 25 % in the trained group, compared to a difference of only 2 % in the control group of nine athletes. The authors concluded that this may represent a clinically significant finding. There were some exercises that were too physically difficult for the athletes to perform correctly and modifications to the protocol regarding frequency and intensity were suggested for future studies.

In a study discussed previously, DiStafano et al. [8] reported no significant improvement in LESS scores in subjects 10–13 years old after ACL intervention training (see also section "Effect of Age, Gender, and ACL Training Program on Landing Technique"). In response to these findings, DiStefano and associates [9, 10] developed and assessed the effects of a pediatric intervention training program in soccer players (boys and girls) who were 9–10 years old on balance, vertical jump height, and biomechanics of a side-step cutting task. The subjects were randomly assigned to conduct either a standard neuromuscular protocol or the pediatric program which differed in exercise intensity and progression. Both programs were 10–15 min warm-up protocols that were performed 3 days a week for 9 weeks. In one study [9], the traditional neuromuscular program resulted in positive changes in 1 balance index (anterior-posterior time to stabilization, $P = .003$) and vertical jump height (mean 1.70 ± 2.80 cm, $P = .04$), while the pediatric program failed to produce any significant improvements. In a second study [10], the pediatric program resulted in significantly less knee external rotation at initial ground contact ($P = .03$) and greater knee internal rotation during stance phase of a cutting task ($P = .01$) compared with the control group. However, there were no differences between the two programs or between either program and the control group for knee flexion, knee varus, hip extension, hip adduction, and hip internal rotation at initial contact or stance phase. The authors concluded that the programs had limited effectiveness in improving lower extremity cutting biomechanics in subjects who were <12 years old.

Critical Points

- Vertical jump height: improved in seven studies, no improvement in six studies
- Single-leg hop: distance hopped improved in four studies
- Sprint tests: mixed results
- Estimated VO_2max: improved in three studies
- Abdominal strength and endurance: improved in two studies

References

1. Arnason A, Engebretsen L, Bahr R (2005) No effect of a video-based awareness program on the rate of soccer injuries. Am J Sports Med 33(1):77–84
2. Barber-Westin SD, Hermeto AA, Noyes FR (2010) A 6-week neuromuscular training program for competi-

tive junior tennis players. J Strength Cond Res 24(9):2372–2382
3. Barber-Westin SD, Smith ST, Campbell T et al (2010) The drop-jump video screening test: retention of improvement in neuromuscular control in female volleyball players. J Strength Cond Res 24(11):3055–3062
4. Barendrecht M, Lezeman HC, Duysens J et al (2011) Neuromuscular training improves knee kinematics, in particular in valgus aligned adolescent team handball players of both sexes. J Strength Cond Res 25(3): 575–584
5. Caraffa A, Cerulli G, Projetti M et al (1996) Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. Knee Surg Sports Traumatol Arthrosc 4(1):19–21
6. Chappell JD, Limpisvasti O (2008) Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. Am J Sports Med 36(6): 1081–1086
7. Chimera NJ, Swanik KA, Swanik CB et al (2004) Effects of plyometric training on muscle-activation strategies and performance in female athletes. J Athl Train 39(1):24–31
8. DiStefano LJ, Padua DA, DiStefano MJ et al (2009) Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. Am J Sports Med 37(3):495–505
9. Distefano LJ, Padua DA, Blackburn JT et al (2010) Integrated injury prevention program improves balance and vertical jump height in children. J Strength Cond Res 24(2):332–342
10. DiStefano LJ, Blackburn JT, Marshall SW et al (2011) Effects of an age-specific anterior cruciate ligament injury prevention program on lower extremity biomechanics in children. Am J Sports Med 39(5):949–957
11. Ettlinger CF, Johnson RJ, Shealy JE (1995) A method to help reduce the risk of serious knee sprains incurred in alpine skiing. Am J Sports Med 23(5):531–537
12. Gilchrist J, Mandelbaum BR, Melancon H et al (2008) A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. Am J Sports Med 36(8):1476–1483
13. Grandstrand SL, Pfeiffer RP, Sabick MB et al (2006) The effects of a commercially available warm-up program on landing mechanics in female youth soccer players. J Strength Cond Res 20(2):331–335
14. Griffin LY, Albohm MJ, Arendt EA et al (2006) Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. Am J Sports Med 34(9):1512–1532
15. Heidt RS Jr, Sweeterman LM, Carlonas RL et al (2000) Avoidance of soccer injuries with preseason conditioning. Am J Sports Med 28(5):659–662
16. Herman DC, Weinhold PS, Guskiewicz KM et al (2008) The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. Am J Sports Med 36(4):733–740
17. Herman DC, Onate JA, Weinhold PS et al (2009) The effects of feedback with and without strength training on lower extremity biomechanics. Am J Sports Med 37(7):1301–1308
18. Herrington L (2010) The effects of 4 weeks of jump training on landing knee valgus and crossover hop performance in female basketball players. J Strength Cond Res 24(14):3427–3432
19. Hewett TE, Stroupe AL, Nance TA et al (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24(6):765–773
20. Hewett TE, Lindenfeld TN, Riccobene JV et al (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27(6):699–706
21. Holm I, Fosdahl MA, Friis A et al (2004) Effect of neuromuscular training on proprioception, balance, muscle strength, and lower limb function in female team handball players. Clin J Sport Med 14(2):88–94
22. Hurd WJ, Chmielewski TL, Snyder-Mackler L (2006) Perturbation-enhanced neuromuscular training alters muscle activity in female athletes. Knee Surg Sports Traumatol Arthrosc 14(1):60–69
23. Irmischer BS, Harris C, Pfeiffer RP et al (2004) Effects of a knee ligament injury prevention exercise program on impact forces in women. J Strength Cond Res 18(4):703–707
24. Junge A, Rosch D, Peterson L et al (2002) Prevention of soccer injuries: a prospective intervention study in youth amateur players. Am J Sports Med 30(5): 652–659
25. Kato S, Urabe Y, Kawamura K (2008) Alignment control exercise changes lower extremity movement during stop movements in female basketball players. Knee 15(4):299–304
26. Labella CR, Huxford MR, Grissom J et al (2011) Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. Arch Pediatr Adolesc Med 165(11):1033–1040
27. Leger LA, Lambert J (1982) A maximal multistage 20-m shuttle run test to predict VO_2 max. Eur J Appl Physiol Occup Physiol 49(1):1–12
28. Lephart SM, Abt JP, Ferris CM et al (2005) Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. Br J Sports Med 39(12):932–938
29. Lim BO, Lee YS, Kim JG et al (2009) Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. Am J Sports Med 37(9):1728–1734
30. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010
31. McLeod TC, Armstrong T, Miller M et al (2009) Balance improvements in female high school

basketball players after a 6-week neuromuscular-training program. J Sport Rehabil 18(4):465–481
32. Myer GD, Ford KR, Palumbo JP et al (2005) Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. J Strength Cond Res 19(1):51–60
33. Myer GD, Ford KR, McLean SG et al (2006) The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. Am J Sports Med 34(3):445–455
34. Myer GD, Ford KR, Brent JL et al (2007) Differential neuromuscular training effects on ACL injury risk factors in"high-risk" versus "low-risk" athletes. BMC Musculoskelet Disord 8:39
35. Myklebust G, Engebretsen L, Braekken IH et al (2003) Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. Clin J Sport Med 13(2):71–78
36. Nagano Y, Ida H, Akai M et al (2011) Effects of jump and balance training on knee kinematics and electromyography of female basketball athletes during a single limb drop landing: pre-post intervention study. Sports Med Arthrosc Rehabil Ther Technol 3(1):14
37. 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
38. Noyes FR, Barber-Westin SD, Smith ST et al (2011) A training program to improve neuromuscular indices in female high school volleyball players. J Strength Cond Res 25(8):2151–2160
39. Noyes FR, Barber-Westin SD, Smith ST et al (2012) A training program to improve neuromuscular and performance indices in female high school basketball players. J Strength Cond Res 26(3):709–719
40. Noyes FR, Barber-Westin SD, Smith ST et al (2012) A training program to improve neuromuscular and performance indices in female high school soccer players. J Strength Cond Res. Epub ahead of print, March 4, 2012
41. Olsen OE, Myklebust G, Engebretsen L et al (2005) Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. BMJ 330(7489):449
42. Pasanen K, Parkkari J, Pasanen M et al (2008) Neuromuscular training and the risk of leg injuries in female floorball players: cluster randomised controlled study. BMJ 337:a295
43. Paterno MV, Myer GD, Ford KR et al (2004) Neuromuscular training improves single-limb stability in young female athletes. J Orthop Sports Phys Ther 34(6):305–316
44. Petersen W, Zantop T, Steensen M et al (2002) Prevention of lower extremity injuries in handball: initial results of the handball injuries prevention programme. Sportverletz Sportschaden 16(3):122–126
45. Petersen W, Braun C, Bock W et al (2005) A controlled prospective case control study of a prevention training program in female team handball players: the German experience. Arch Orthop Trauma Surg 125(9):614–621
46. Pfeiffer RP, Shea KG, Roberts D et al (2006) Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. J Bone Joint Surg Am 88(8): 1769–1774
47. Pollard CD, Sigward SM, Ota S et al (2006) The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. Clin J Sport Med 16(3): 223–227
48. Ramsbottom R, Brewer J, Williams C (1988) A progressive shuttle run test to estimate maximal oxygen uptake. Br J Sports Med 22(4):141–144
49. Renstrom P, Ljungqvist A, Arendt E et al (2008) Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. Br J Sports Med 42(6):394–412
50. Sadoghi P, von Keudell A, Vavken P (2012) Effectiveness of anterior cruciate ligament injury prevention training programs. J Bone Joint Surg Am 94(9):769–776
51. Sigward S, Pollard CD, Powers CM (2008) Abstract #29. The influence of an ACL injury prevention program on knee valgus moments during cutting: an evaluation of pre-pubertal, pubertal and post-pubertal female athletes. J Athl Train 43(5):559
52. Soderman K, Werner S, Pietila T et al (2000) Balance board training: prevention of traumatic injuries of the lower extremities in female soccer players? A prospective randomized intervention study. Knee Surg Sports Traumatol Arthrosc 8(6):356–363
53. Soligard T, Myklebust G, Steffen K et al (2008) Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. BMJ 337:a2469
54. Steffen K, Bakka HM, Myklebust G et al (2008) Performance aspects of an injury prevention program: a ten-week intervention in adolescent female football players. Scand J Med Sci Sports 18(5):596–604
55. Steffen K, Myklebust G, Olsen OE et al (2008) Preventing injuries in female youth football – a cluster-randomized controlled trial. Scand J Med Sci Sports 18(5):605–614
56. Tsang KK, Dipasquale AA (2011) Improving the q:h strength ratio in women using plyometric exercises. J Strength Cond Res 25(10):2740–2745
57. Vescovi JD, Canavan PK, Hasson S (2008) Effects of a plyometric program on vertical landing force and jumping performance in college women. Phys Ther Sport 9(4):185–192
58. Vescovi JD, VanHeest JL (2010) Effects of an anterior cruciate ligament injury prevention program on performance in adolescent female soccer players. Scand J Med Sci Sports 20(3):394–402
59. Wedderkopp N, Kaltoft M, Lundgaard B et al (1999) Prevention of injuries in young female players in

European team handball. A prospective intervention study. Scand J Med Sci Sports 9(1):41–47
60. Wilderman DR, Ross SE, Padua DA (2009) Thigh muscle activity, knee motion, and impact force during side-step pivoting in agility-trained female basketball players. J Athl Train 44(1):14–25
61. Wilkerson GB, Colston MA, Short NI et al (2004) Neuromuscular changes in female collegiate athletes resulting from a plyometric jump-training program. J Athl Train 39(1):17–23
62. Wojtys EM, Huston LJ, Taylor PD et al (1996) Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. Am J Sports Med 24(2):187–192
63. Yoo JH, Lim BO, Ha M et al (2010) A meta-analysis of the effect of neuromuscular training on the prevention of the anterior cruciate ligament injury in female athletes. Knee Surg Sports Traumatol Arthrosc 18(6):824–830
64. Zebis MK, Bencke J, Andersen LL et al (2008) The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. Clin J Sport Med 18(4):329–337

Part V

Reducing the Risk of Reinjury After ACL Reconstruction

Rehabilitation After ACL Reconstruction

19

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

Contents

T.P. Heckmann, P.T., A.T.C. (✉) • F.R. Noyes, M.D.
Cincinnati Sportsmedicine and Orthopaedic Center, 10663 Montgomery Road, Cincinnati, OH 45242, USA

Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, OH 45242, USA
e-mail: theckmann@csmoc.com

S.D. Barber-Westin, B.S.
Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

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 that followed patients for a minimum of 5 years after ACL reconstruction revealed reinjury rates ranging from 7 to 40 % [1, 9, 10, 15, 18, 23, 24, 28, 31–33, 36]. These rates included either a rupture to the ACL graft or an injury to the contralateral ACL. To date, factors identified with increased reinjury risk are younger-aged athletes [15, 28, 33, 36], vertical ACL graft orientation [15], and return to sports with well-documented high rates of ACL injury such as soccer, basketball, and team handball [23, 36]. ACL reconstructions may also fail for other reasons such as surgical errors (use of

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_19, © Springer-Verlag Berlin Heidelberg 2012

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. A systematic review was conducted to examine the factors investigators have used over the last decade to determine when return to unrestricted athletics is appropriate [4]. The inclusionary criteria for the review were original research clinical investigations on primary ACL reconstructions published in the English language in the last 10 years, all adult populations, and a minimum of 12 months of follow-up. Of 716 studies initially identified, 264 met the study inclusionary criteria. Of these, 105 (40 %) failed to provide any criteria for return to sports after surgery. In 84 studies (32 %), the amount of time that elapsed postoperatively was the only criteria mentioned. In 40 (15 %) studies, the amount of time postoperative along with subjective (not measurable) criteria were given.

Only 35 studies (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.

The authors 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 [2], failure to address and fully rehabilitate both knees may also be a factor for high postoperative reinjury rates. This chapter provides the authors' recommendations for exercises and goals for each phase of rehabilitation as well as extensive criteria required for release to high-level athletics, based on nearly three decades of experience and multiple clinical studies [26].

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 [14]. 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 [17, 34, 35]. 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 [6, 39]. 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.

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 [13, 22, 27, 37]. ACL reconstruction followed by traditional strength training may not correct these abnormalities [5, 11, 19, 21]. Therefore, neuromuscular retraining is recognized as an essential component of ACL rehabilitation programs [14, 29, 30, 33, 38]. Early studies that evaluated balance and perturbation training following ACL rupture reported improved results compared to traditional strength training programs [7, 12, 16, 20]. Barrett [5] in 1991 emphasized the importance of reestablishing normal proprioception following ACL reconstruction. Risberg et al. [29] identified the need to restore both mechanical stability and neuromuscular control to achieve a long-term successful outcome. These authors advocated neuromuscular retraining to improve the central nervous system's ability to generate a fast and optimal muscle firing pattern, increase dynamic joint stability, decrease joint forces, and relearn movement patterns and skills required for daily and sports activities.

At the authors' 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; the concomitant operative procedures performed with the ACL reconstruction; the type of graft used; the postoperative healing and response to surgery; and the 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 [14].

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 as described elsewhere [14].

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

Early Postoperative Rehabilitation: Weeks 1–6

The overall goals for the early phases of rehabilitation are to control pain and swelling, regain at least 0–135° of knee motion, resume full weight bearing with a normal gait pattern, and recover adequate strength of the lower extremity and hip musculatures (Table 19.1). This is the time period to recognize and treat early postoperative

Table 19.1 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: 0–135° 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: full Muscle control: 4/5 Full weight bearing, normal gait 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 week): ≤30 % deficit quadriceps and hamstrings No pain, swelling, patellofemoral crepitus Lachman, KT-2000 arthrometer test <3 mm increase over opposite side Begin running (straight ahead) program
VI Weeks 13–26	Isokinetic test (isometric, 300°/s): 20–25 % deficit quadriceps and hamstrings No pain, swelling, patellofemoral crepitus Lachman, KT-2000 arthrometer test <3 mm increase over opposite side Single-leg hop tests: 25 % deficit compared to uninvolved limb Continue running program, begin cutting program, basic plyometric training
VII Week 27–beyond	Enter advanced neuromuscular retraining when: Isokinetic test (180°/s, 300°/s): < 20 % deficit quadriceps and hamstrings No pain, swelling, patellofemoral crepitus Lachman, KT-2000 arthrometer test <3 mm increase over opposite side Single-leg hop function tests: <15 % deficit compared to uninvolved limb Successful completion running program Successful completion beginning plyometric training with therapy staff

ROM range of motion, *KT* knee arthrometer

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 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 19.2). 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,

Table 19.2 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: immobilizer for patient comfort	X	(X)							
Range of motion minimum goals:									
0–110°	X								
0–120°		X							
0–135°			X						
Weight bearing:									
1/2 body weight	X								
Full		X							
Patella mobilization	X	X	X						
Modalities:									
Electrical muscle stimulation	X	X	X						
Biofeedback	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
Strengthening:									
Quadriceps isometrics, straight leg raises, active knee extension, mini-squats	X	X	X	X	X				
Closed-chain: toe raises, heel raises, wall sits		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 (70–10°)	X	X	X	X	X	X	X	X	X
Balance/proprioceptive training:									
Weight shifting, cup walking	X	X							
Balance board, single-leg stance		X	X	X	X	X	X	X	X
Lateral step-ups			X	X	X				
Resistance band walking, perturbation training, ball toss mini-trampoline				X	X				
Conditioning:									
Upper body strength program		X	X	X	X	X	X	X	X
Core strength program		X	X	X	X	X	X	X	X
Bike (stationary)		X	X	X	X	X	X	X	X
Aquatic program		X	X	X	X	X	X	X	X
Swimming (kicking)				X	X	X	X	X	X
Walking				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
Elliptical machine				X	X	X	X	X	X
Running: straight					X	X	X	X	X
Cutting: lateral carioca, figure-8's						X	X	X	X
Plyometric training						X	X	X	X

Fig. 19.1 Passive range of knee motion exercises done by (**a**–**c**) the patient or (**d**) the therapist

achieve an adequate quadriceps contraction, and regain normal knee flexion and extension.

The protocol for prevention of deep venous thrombosis includes 1–2 aspirin a day for 5 days and use of a bulky compression dressing for 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 3–5 days postoperative.

Patients begin passive- and active-assisted knee motion exercises the first day postoperatively in a seated position for 10 min a session, 4–6 times a day (Fig. 19.1). 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. 19.2). At least 0° of knee extension should be obtained by the second week (Table 19.3). Knee flexion is gradually increased to 135° by the third to fourth week.

Patients who fail to achieve these motion goals should be placed into the treatment protocols shown in Table 19.4 [25]. 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

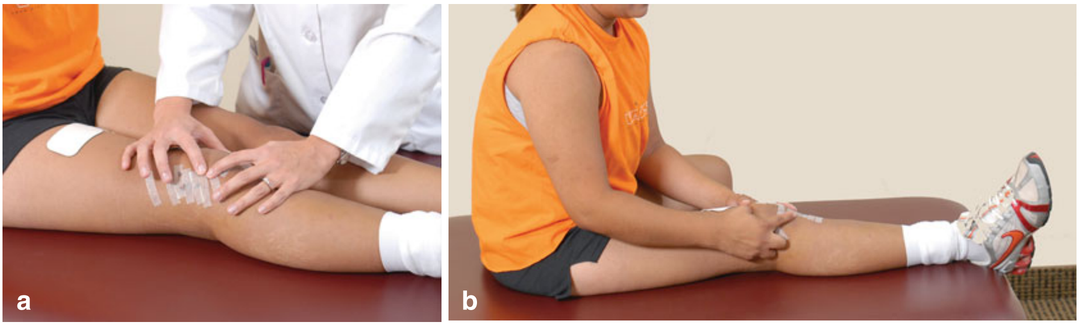


Fig. 19.2 Patella mobilization performed by (**a**) the therapist or (**b**) the patient

Table 19.3 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	4–6×/day	Medial-lateral superior-inferior	Hamstring, gastroc-soleus	Yes	Yes	Yes
3–4 weeks	3–4×/day	Medial-lateral superior-inferior	Hamstring, gastroc-soleus	Yes	As required	Yes
5–6 weeks	3×/day	Medial-lateral superior-inferior	Hamstring, gastroc-soleus	As required		Yes
7 weeks–beyond		Should be normal	Hamstring, gastroc-soleus, quadriceps, iliotibial band			Yes

propped on a towel or other device to elevate the hamstrings and gastrocnemius (Fig. 19.3). This position is maintained for 10 min per session and repeated 4–6 times a day. Weight (up to 20 lb, 9 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. 19.4). Failure to obtain full knee motion will greatly hinder the patient's ability to reach other rehabilitation goals, and therefore, any problems achieving flexion and extension should be addressed during the 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 [25].

An immobilizer may be used during the first few postoperative weeks to protect the patient in case of a fall and to begin early, more comfortable weight bearing. The hinged brace allows 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 19.5). Closed kinetic chain exercises are initiated the first postoperative week, including mini-squats, transitional wall sits, and the leg press machine (Fig. 19.5). 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.

Table 19.4 Protocols for limitation of knee motion [25]

Extension limitations:
0° not achieved by seventh postoperative day
Hanging weight exercise: while seated, 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 weight to the distal thigh to provide overpressure to stretch the posterior capsule.
Maintain for 10 min and repeat 4–6×/day.
Add more weight (≤11 kg) 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 fourth postoperative week
Gentle manipulation under anesthesia
<90° flexion sixth postoperative week
Arthroscopic release of contracted scar tissues

Fig. 19.3 Overpressure extension exercises using (**a**) a hanging weight and (**b**) an extension board. The photographs show the patient seated; however, we prefer the supine position if possible to increase the stretch. A drop-out cast (**c**) may be used for resistant cases

Fig. 19.3 (continued)

Fig. 19.4 Overpressure flexion exercises using (**a**, **b**) wall sliding technique and (**c**, **d**) commercially available knee flexion devices

Table 19.5 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 (70–10°)
1–2 weeks, 3×/day, 15 min	1 set × 10 reps every hour patient is awake	All 4 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×/day, 20 min	Multiangle: 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, 2×/day, 20 min	Multiangle: 30°, 60°, 90° 2 sets × 10 reps each angle	With ankle weight (≤10 % of body weight): 3 sets × 10 reps With rubber tubing: 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, 2×/day, 20 min		With rubber tubing: 3 sets × 30 reps	With resistance: 3 sets × 10 reps	3 sets ×, 20 reps	5 reps	3 sets × 20 reps	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps
9–12 weeks, 2×/day, 20 min		With rubber tubing: 3 sets × 30 reps	With resistance: 3 sets × 10 reps	3 sets ×, 20 reps	5 reps	3 sets × 20 reps	3 sets × 10 reps	3 sets × 10 reps	3 sets × 10 reps
13–26 weeks, 1×/day, 20–30 min		Rubber tubing, 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, 1–2×/week, 20–30 min		Rubber tubing, 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

Open kinetic chain extension exercises are also begun within the first few weeks to further develop quadriceps muscle strength. Caution is warranted due to the potential problems these exercises may create for the healing graft and the patellofemoral joint. Resistance in the terminal phase of open kinetic chain extension (0–30°) is avoided 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. 19.6), using a side-lying "clam" exercise with (or without) a resistance band (Fig. 19.7), walking with exaggerated hip flexion with (or without) a resistance band (Fig. 19.8), and ambulating with lateral lunges 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 progressing to the running program and is recovered using toe raises and heel raises, beginning with both feet together (Fig. 19.9) and progressing to single-leg raises.

Balance and proprioceptive training are initiated the first postoperative week (Table 19.6). 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. 19.10a). Half foam rolls are also used as part of the gait retraining and balance program (Fig. 19.10b). 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 in. (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 19.7). Stationary bicycling is begun during the third week. Water walking may be initiated when the surgical wound has healed. Early goals of these programs include facilitation of full range of motion, gait retraining, and cardiovascular reconditioning. In order to improve cardiovascular endurance, the program should be performed at least 3 times/week for 20–30 min, and the exercise performed to at least 60–85 % of maximal heart rate.

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 and low resistance.

Critical Points

- Goals: control pain and swelling, regain 0–135°, assume full weight bearing with normal gait, regain strength of lower extremity.
- Recognize and treat problems early postoperatively.
- First postoperative week critical: control pain and swelling, demonstrate adequate quadriceps contraction, 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.

Fig. 19.5 Closed kinetic chain exercises begun the first postoperative week include (**a**) mini-squats, (**b**) wall sits, and (**c**) the leg press machine. The mini-squats and wall sits should be done with shoes on if the floor is slippery or the feet cannot remain in a stable position for the exercise.

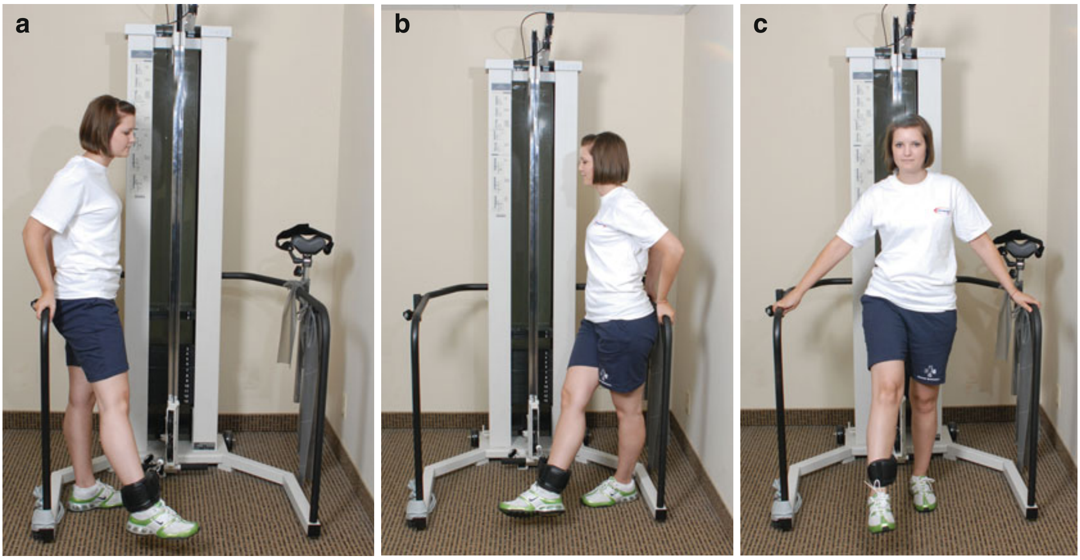


Fig. 19.6 The hip abductors (**a**), adductors (**b**), and flexor (**c**) muscle groups exercised on a cable system machine

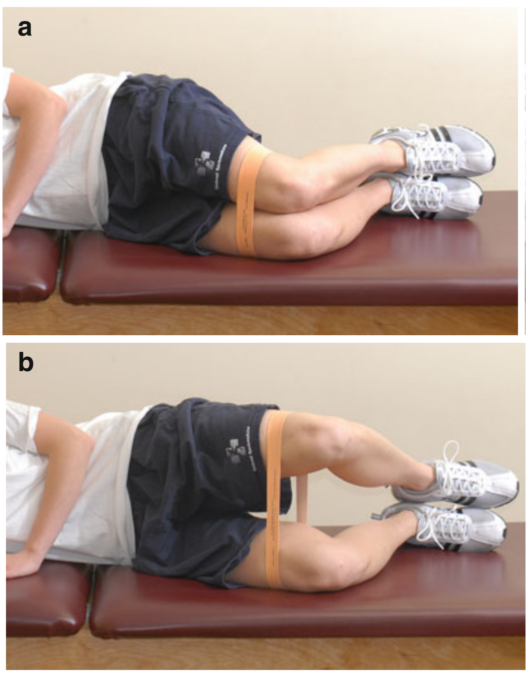


Fig. 19.7 The hip abductors exercised using a side-lying "clam" exercise which may be performed with (**a–b**) or without a resistance band

Fig. 19.8 Walking with exaggerated hip flexion may be done with or without a resistance band

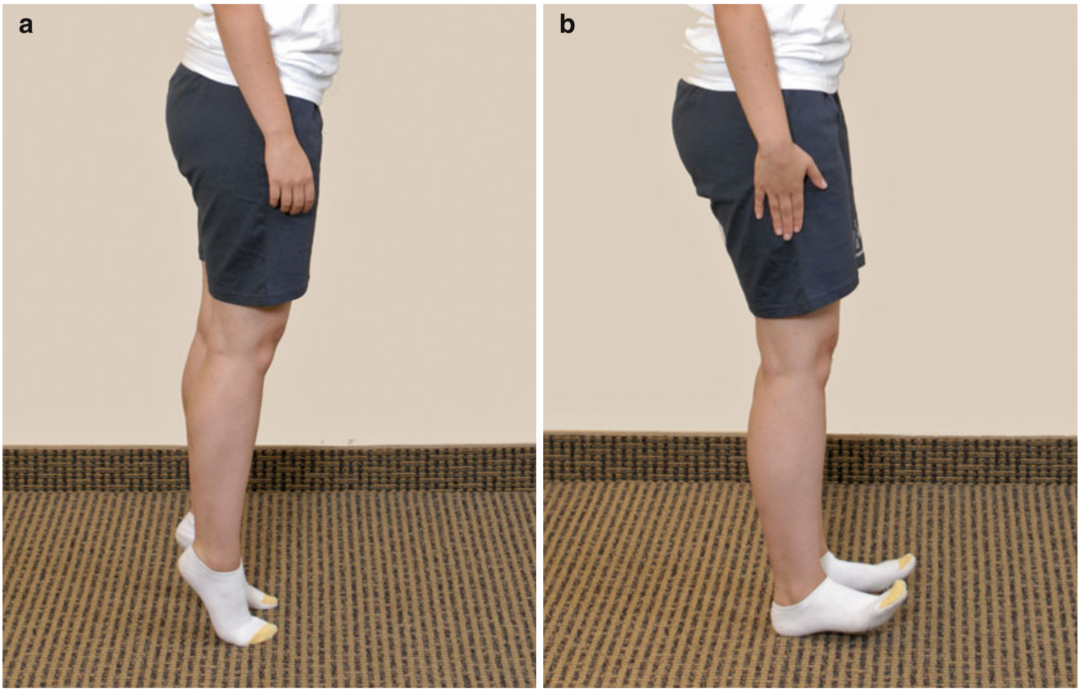


Fig. 19.9 Strength of the gastrocnemius and soleus muscles initially recovered using (**a**) toe raises and (**b**) heel raises

Table 19.6 Balance and proprioception exercises

Time postop	Frequency, duration	Weight shifting	Balance board	Cup walking	Single-leg stance	Lateral step-ups	Resistance band walking	Plyoback ball toss	Perturbation training
1–2 weeks	3×/day, 5 min	Side-side and forward-backward 5 sets × 10 reps		Start					
3–4 weeks	3×/day, 5 min	Side-side and forward-backward 5 sets × 10 reps	2-legged	Perform	Level surface 5 reps				
5–6 weeks	3×/day, 5 min		2-legged		Level surface	Start			
7–8 weeks	3×/day, 5 min		Single leg		Level surface	Continue	Start	Start	Start
9–12 weeks	3×/day, 5 min		Single leg		Level surface	Continue	Continue	Continue	Continue
13–26 weeks	3×/day, 5 min		Single leg		Unstable platform		Continue		Continue
27 weeks –beyond			Single leg		Unstable platform with secondary activity				

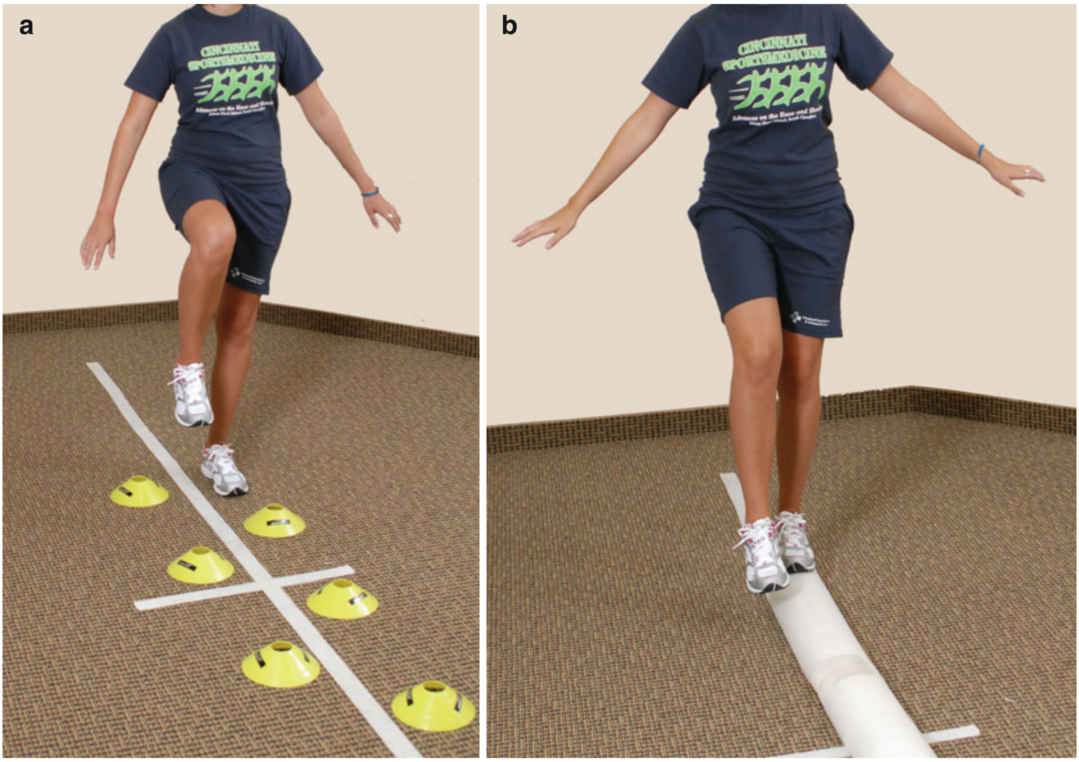


Fig. 19.10 The early gait retraining and balance program includes walking (**a**) over cups or cones and (**b**) on half foam rolls

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 range of knee motion with normal patellar mobility; and begin the running program if specific criteria are achieved (see Sect. 19.5).

Muscle strengthening exercises are progressed as shown in Table 19.5. 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. 19.11a, 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. 19.11c). They may also perform single-leg hops in specific directions by balancing first on the normal contralateral limb (Fig. 19.12a), hopping and landing on the reconstructed limb (Fig. 19.12b), and then returning to the starting position, balanced on the normal limb (Fig. 19.12c).

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 platform periodically to enhance dynamic knee stability (Fig. 19.13). Aerobic conditioning continues and patients are encouraged to spend at least 3 days a week in 20-min sessions using either a stationary bicycle, stair machine, ski machine, elliptical machine, or swimming.

Table 19.7 Aerobic conditioning exercisesa

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×/day, 5 min	OK										
3–4 weeks, 2×/day, 5 min	OK	OK	OK								
5–6 weeks, 2×/day, 10 min	OK	OK	OK			OK	OK				
7–8 weeks, 1–2×/day, 15–20 min		OK	OK	OK	OK	OK	OK	OK			
9–12 weeks, 3×/week, 15–20 min		OK	OK	OK	OK	OK	OK	OK	Begin if conditions are met[a]		
13–26 weeks, 3×/week, 15–20 min		OK	OK	OK	OK	OK	OK	OK	Progress	Begin if conditions are met[a]	Box hops, level, double-leg 15 s if conditions are met
27 weeks –beyond, 3×/week, 20–30 min		OK	OK	OK	OK	OK	OK		Progress	Progress	Begin Sportsmetrics program if conditions are met

[a]Patient selects one exercise for each session

Fig. 19.11 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

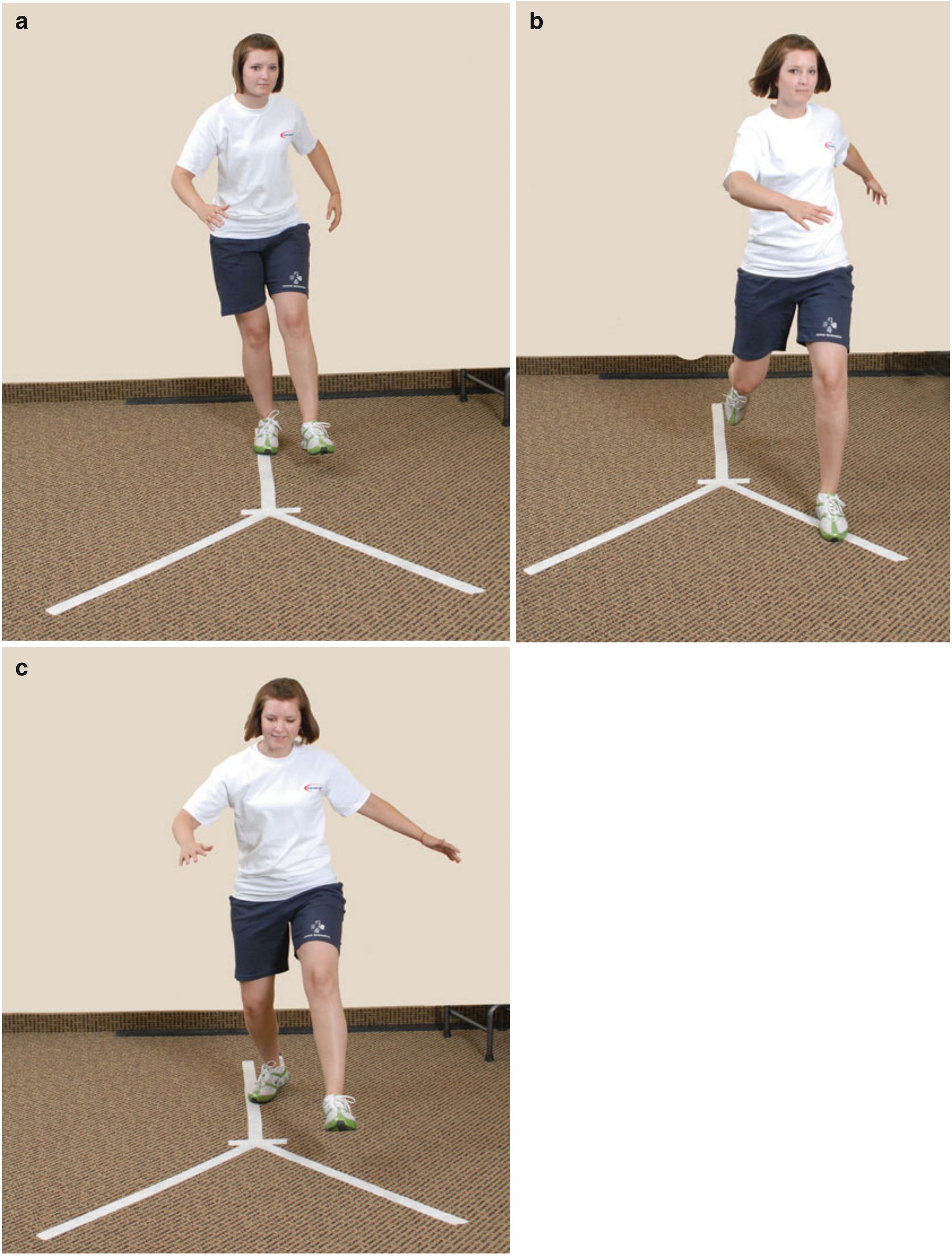


Fig. 19.12 Single-leg directional hopping and balancing (**a**–**c**)

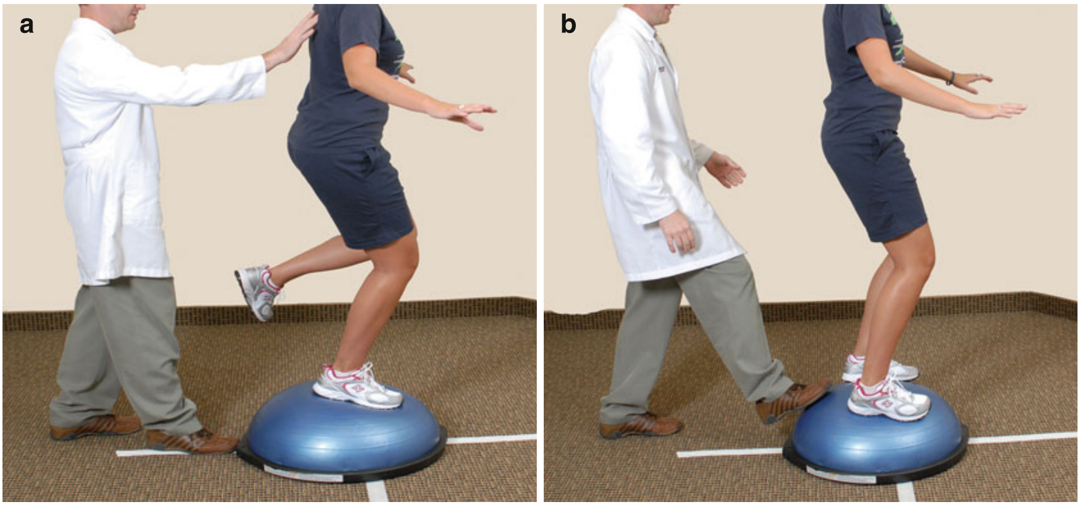


Fig. 19.13 Perturbation training performed by using direct contact with either the (**a**) patient or (**b**) platform

Critical Points
- Goals: improve muscle strength; no pain, swelling, and giving-way; full range of motion; and normal patellar mobility
- Perturbation training incorporated for balance, neuromuscular control
- Aerobic conditioning 3 days a week

Intensive Training Phase: Weeks 13–Beyond

The goals of this phase of rehabilitation are to restore 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 of patients are 16–20 weeks postoperative.

Muscle strengthening exercises are continued with weight machines 3 times/week. Aerobic conditioning is advanced as tolerated 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: restore normal strength, balance, proprioception, running speed, 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

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 3 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. The following criteria must be met for the patient to begin the running program:

- ≤30 % deficit quadriceps and hamstrings peak torque on isokinetic test.
- <3 mm increased anteroposterior tibial displacement on Lachman, arthrometer test.
- Patient is at least 9 weeks postoperative; usually 16–20 weeks postoperative.
- No pain, swelling, or instability with all other rehabilitation activities.

There are four levels in the running program:

- Level I:
  - Straight-ahead run-walk combinations. Running distances 20, 40, 60, and 100 yd (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 yd (18.29 m)
  - Side-to-side running over cups
  - Sports-specific equipment used to enhance skill development
- Level III:
  - Figure-eight drills over 20 yd (18.29 m) and then decrease to 10 yd (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 week postoperative
- Criteria:
  - ≤30 % deficit isokinetic peak torque of quadriceps, hamstrings
  - Normal Lachman
  - No pain, swelling, instability with all other rehabilitation exercises
- 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

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. 19.14).

Plyometric training is performed 2–3 times weekly. Individual sessions are accomplished in a manner similar to interval training. Initially, the rest period lasts 2–3 times the length of the exercise period which is gradually decreased to 1–2

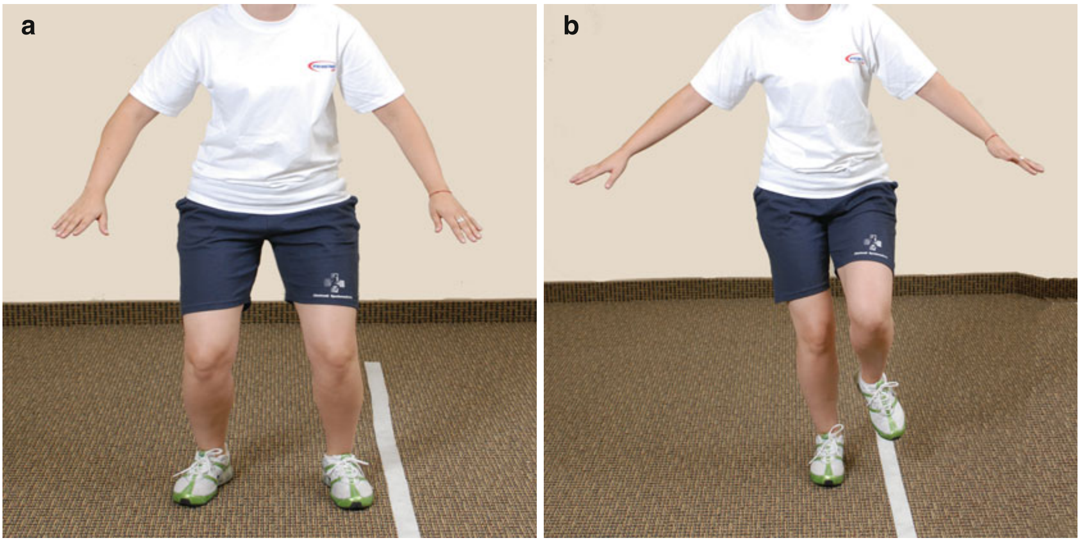


Fig. 19.14 Plyometric training with demonstration of proper landing positions for (**a**) double-leg and (**b**) single-leg jumps

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 is recorded. The program is progressed as the number of hops increases, along with patient confidence. The criteria required to begin basic plyometric training are:

- Successful completion of the running and agility program
- No pain, swelling, or instability with any activity

There are three levels in the basic plyometric training program:

- Level I: level surface box hopping, both legs
  - Front-back
  - Side-side
  - Diagonal (Fig. 19.15)
  - Pivot hops, 90° and 180° directions (Fig. 19.16)
  - Level II: level surface box hopping, single leg
  - Front-back
  - Side-side
  - Diagonal
  - Pivot hops, 90° and 180° directions
- Level III: vertical box hops

Critical Points

- Begun after successful completion of running program
- Avoid very hard surfaces
- Proper mechanics, body position emphasized
- Level surface box hops, use both legs, 4-square grid
- Progress to single-leg hops, vertical box hops
- Perform 2–3 times/week

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 (such as soccer or basketball) following 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

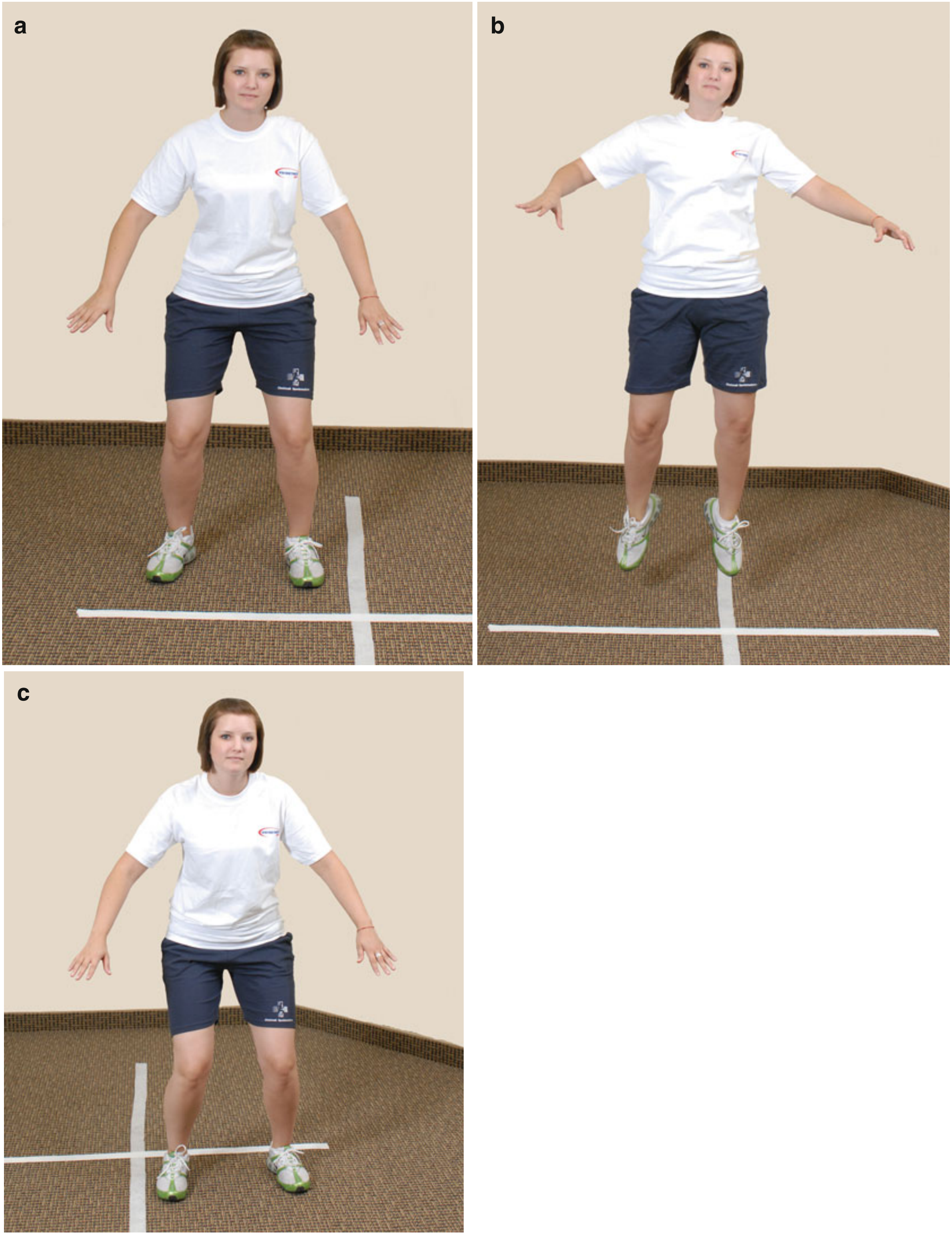


Fig. 19.15 Beginning plyometrics, Level I: level surface box hopping using both legs in a diagonal pattern (**a**–**c**)

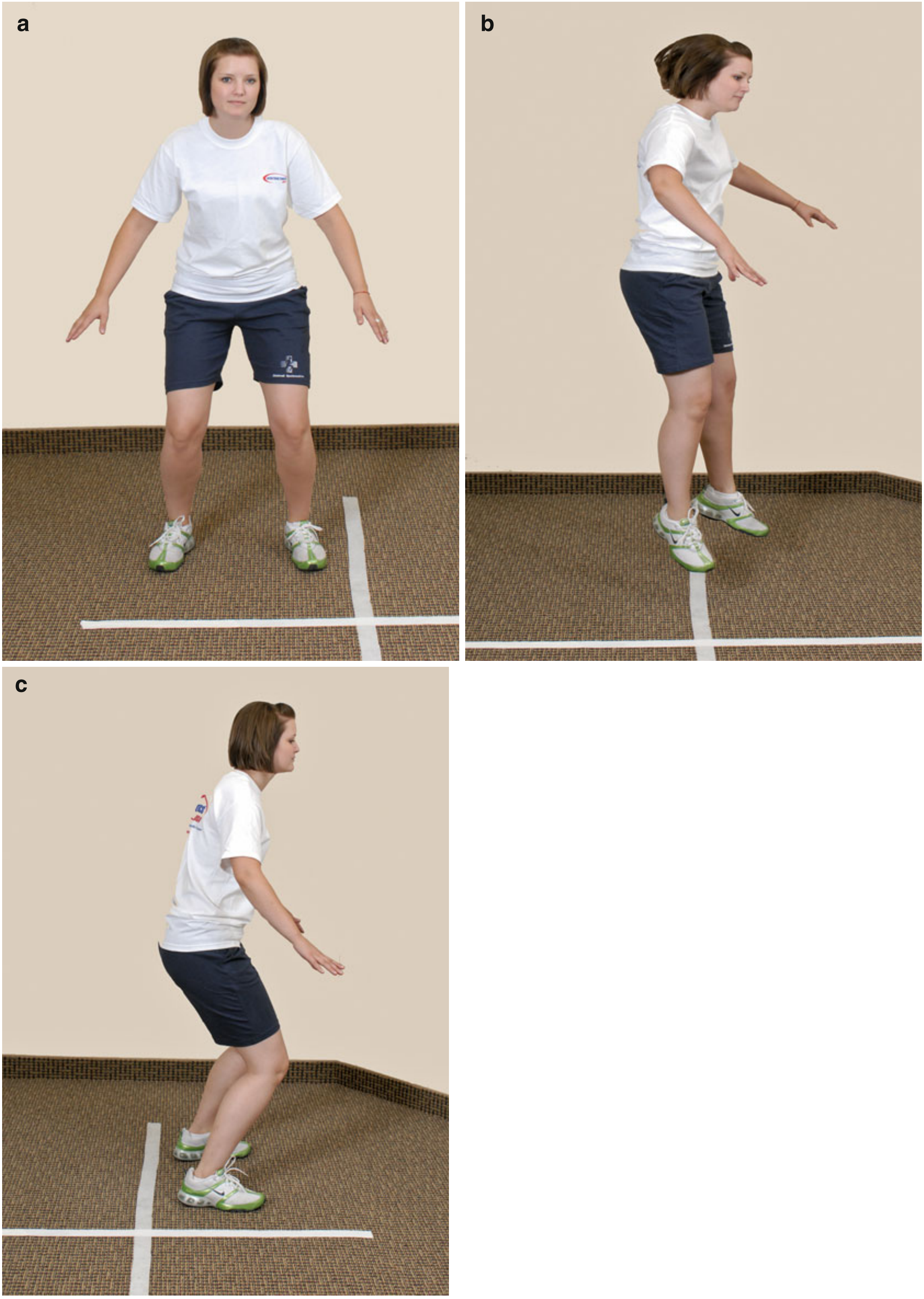


Fig. 19.16 Beginning plyometrics, Level I: level surface box hopping using both legs in a 90° pattern (**a**–**c**)

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 range of knee motion
- ≤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 patient and instructs them on the jumps in phase 1. The videotape is also used for demonstration and further education regarding how to perform each jump and the usual corrections required.
2. The patient practices the jumps during the next 7 days.
3. The physical therapist or trainer and patient meet the next week and the patient demonstrates the jumps. If done correctly, training begins. The patient completes phase 1 over next 2 weeks. The patient records the jumps done on the training logs for each session.
4. The physical therapist or trainer and patient meet in 2 weeks. The patient must master the jumps in phase 1 before entering into phase 2. If extra time is required, this is built in according to the therapist's or trainer's recommendations.
5. Upon completion of phase 2, the physical therapist or trainer teaches the patient the jumps in phase 3. The patient completes phase 3 over next 2 weeks.
6. The physical therapist or trainer and patient meet 2 weeks later to determine if 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 3 stages of training for technique instruction.
- Extra time may be required to complete each phase of training.

Release to Unrestricted Sports Activities

The following criteria are used for release of the patient to unrestricted athletic activities (Fig. 19.17) [3, 4]:

1. Successful completion of phase 3 of Sportsmetrics training program
2. Normal knee stability (negative pivot-shift test, ≤3 mm increase anteroposterior tibial displacement on Lachman test or knee arthrometer test)
3. Full range of knee motion, no joint effusion, normal patellar mobility
4. No pain, swelling, or instability with any activity

Fig. 19.17 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

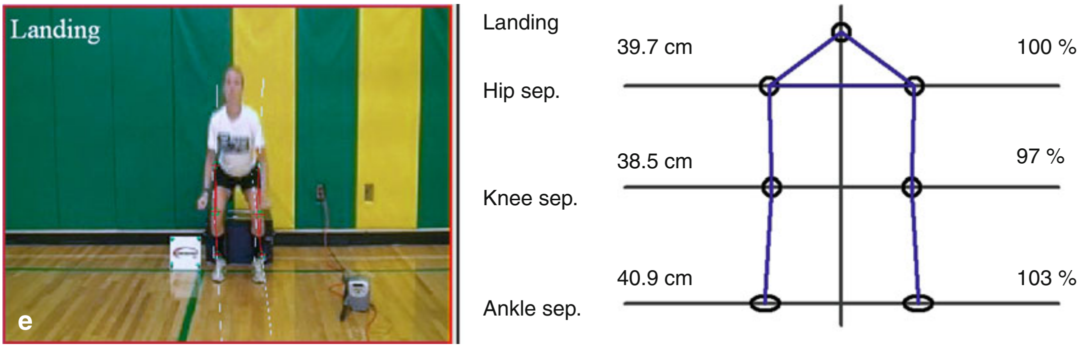


Fig. 19.17 (continued)

5. ≤10 % deficit peak torque hamstrings and quadriceps on isokinetic test (180°/s and 300°/s)
6. ≤15 % deficit distance hopped on single-leg timed and triple crossover hop tests
7. >60 % normalized knee separation distance on video drop-jump test
8. No valgus motion of knee or medial-lateral movement of knee on a single-leg squat test [8]

Each patient performs additional cardiovascular endurance, sports-specific agility, and skill drills as required. A trial of function is recommended during which the patient is monitored for knee pain, swelling, overuse symptoms, and giving-way episodes. The patient is educated to notify medical staff of these problems if they occur.

Critical Points

- Criteria:
  - 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-leg timed hop, single-leg triple hop
  - >60 % normalized knee separation distance video drop-jump test

References

1. Ait Si Selmi T, Fithian D, Neyret P (2006) The evolution of osteoarthritis in 103 patients with ACL reconstruction at 17 years follow-up. Knee 13(5):353–358
2. Barber-Westin SD, Heckmann TP, Noyes FR (2009) Scientific basis of rehabilitation after anterior cruciate ligament autogenous reconstruction. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 268–305
3. Barber-Westin SD, Noyes FR (2011) Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. Phys Sportsmed 39(3):100–110
4. Barber-Westin SD, Noyes FR (2011) Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. Arthroscopy 27(12):1697–1705
5. Barrett DS (1991) Proprioception and function after anterior cruciate reconstruction. J Bone Joint Surg Br 73(5):833–837
6. Beard DJ, Kyberd PJ, Fergusson CM (1993) Proprioception after rupture of the anterior cruciate ligament. An objective indication of the need for surgery? J Bone Joint Surg Br 75(2):311–315
7. Beard DJ, Dodd CAF, Trundle HR et al (1994) Proprioception enhancement for anterior cruciate ligament deficiency. A prospective randomised trial of two physiotherapy regimes. J Bone Joint Surg Br 76(4):654–659
8. Crossley KM, Zhang WJ, Schache AG et al (2011) Performance on the single-leg squat task indicates hip abductor muscle function. Am J Sports Med 39(4):866–873
9. Deehan DJ, Salmon LJ, Webb VJ et al (2000) Endoscopic reconstruction of the anterior cruciate ligament with an ipsilateral patellar tendon autograft. J Bone Joint Surg Br 82(7):984–991
10. Drogset JO, Grontvedt T, Robak OR et al (2006) A sixteen-year follow-up of three operative techniques for the treatment of acute ruptures of the anterior cruciate ligament. J Bone Joint Surg Am 88(5):944–952

11. Fischer-Rasmussen T, Jensen PE (2000) Proprioceptive sensitivity and performance in anterior cruciate ligament-deficient knee joints. Scand J Med Sci Sports 10(2):85–89
12. Fitzgerald GK, Axe MJ, Snyder-Mackler L (2000) The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physical active individuals. Phys Ther 80(2):128–140
13. Gao B, Zheng NN (2010) Alterations in three-dimensional joint kinematics of anterior cruciate ligament-deficient and -reconstructed knees during walking. Clin Biomech (Bristol, Avon) 25(3):222–229
14. Heckmann TP, Noyes FR, Barber-Westin SD (2009) Rehabilitation of primary and revision anterior cruciate ligament reconstructions. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 306–336
15. Hui C, Salmon LJ, Kok A et al (2011) Fifteen-year outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft for "isolated" anterior cruciate ligament tear. Am J Sports Med 39(1):89–98
16. Ihara H, Nakayama A (1986) Dynamic joint control training for knee ligament injuries. Am J Sports Med 14(4):309–315
17. Ingersoll CD, Grindstaff TL, Pietrosimone BG et al (2008) Neuromuscular consequences of anterior cruciate ligament injury. Clin Sports Med 27(3):383–404, vii
18. Keays SL, Bullock-Saxton JE, Keays AC et al (2007) A 6-year follow-up of the effect of graft site on strength, stability, range of motion, function, and joint degeneration after anterior cruciate ligament reconstruction: patellar tendon versus semitendinosus and Gracilis tendon graft. Am J Sports Med 35(5): 729–739
19. Lephart S, Kocher MS, Fu F et al (1992) Proprioception following anterior cruciate ligament reconstruction. J Sport Rehabil 1:188–196
20. Liu-Ambrose T, Taunton JE, MacIntyre D et al (2003) The effects of proprioceptive or strength training on the neuromuscular function of the ACL reconstructed knee: a randomized clinical trial. Scand J Med Sci Sports 13(2):115–123
21. MacDonald PB, Heeden D, Pacin O et al (1996) Proprioception in anterior cruciate ligament-deficient and reconstructed knees. Am J Sports Med 24(6): 774–778
22. Madhavan S, Shields RK (2011) Neuromuscular responses in individuals with anterior cruciate ligament repair. Clin Neurophysiol 122(5):997–1004
23. Myklebust G, Holm I, Maehlum S et al (2003) Clinical, functional, and radiologic outcome in team handball players 6 to 11 years after anterior cruciate ligament injury: a follow-up study. Am J Sports Med 31(6):981–989
24. Nakata K, Shino K, Horibe S et al (2008) Arthroscopic anterior cruciate ligament reconstruction using fresh-frozen bone plug-free allogeneic tendons: 10-year follow-up. Arthroscopy 24(3):285–291
25. Noyes FR, Barber-Westin SD (2009) Prevention and treatment of knee arthrofibrosis. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 1053–1095
26. Noyes FR, Barber-Westin SD (2009) Anterior cruciate ligament primary and revision reconstruction: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR (ed) Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 140–228
27. Orishimo KF, Kremenic IJ, Mullaney MJ et al (2010) Adaptations in single-leg hop biomechanics following anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 18(11):1587–1593
28. Pinczewski LA, Lyman J, Salmon LJ et al (2007) A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: a controlled, prospective trial. Am J Sports Med 35(4):564–574
29. Risberg MA, Mork M, Jenssen HK et al (2001) Design and implementation of a neuromuscular training program following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 31(11):620–631
30. Risberg MA, Holm I (2009) The long-term effect of 2 postoperative rehabilitation programs after anterior cruciate ligament reconstruction: a randomized controlled clinical trial with 2 years of follow-up. Am J Sports Med 37(10):1958–1966
31. Roe J, Pinczewski LA, Russell VJ et al (2005) A 7-year follow-up of patellar tendon and hamstring tendon grafts for arthroscopic anterior cruciate ligament reconstruction: differences and similarities. Am J Sports Med 33(9):1337–1345
32. Sajovic M, Strahovnik A, Komadina R et al (2008) The effect of graft choice on functional outcome in anterior cruciate ligament reconstruction. Int Orthop 32(4):473–478
33. Salmon LJ, Russell VJ, Refshauge K et al (2006) Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. Am J Sports Med 34(5):721–732
34. Schultz RA, Miller DC, Kerr CS et al (1984) Mechanoreceptors in human cruciate ligaments. A histological study. J Bone Joint Surg Am 66(7): 1072–1076
35. Schutte MJ, Dabezies EJ, Zimny ML et al (1987) Neural anatomy of the human anterior cruciate ligament. J Bone Joint Surg Am 69(2):243–247
36. Shelbourne KD, Gray T, Haro M (2009) Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med 37(2):246–251
37. Webster KA, Gribble PA (2010) Time to stabilization of anterior cruciate ligament-reconstructed versus healthy knees in National Collegiate Athletic Association Division I female athletes. J Athl Train 45(6):580–585

38. Wilk KE, Chmielewski TL (2009) Neuromuscular retraining after anterior cruciate ligament reconstruction. In: Noyes FR (ed) Noyes knee disorders: surgery, rehabilitation, clinical outcomes. Saunders, Philadelphia, pp 337–356

39. Wojtys EM, Huston LJ (1994) Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities. Am J Sports Med 22(1): 89–104

Restoration of Proprioception and Neuromuscular Control Following ACL Injury and Surgery

20

Kevin E. Wilk

Contents

K.E. Wilk, P.T., D.P.T., F.A.P.T.A.
Champion Sports Medicine,
806 St. Vincent's Drive, WCC Suite 620,
Birmingham, AL 35205, USA

American Sports Medicine Institute,
Birmingham, AL, USA

Programs in Physical Therapy,
Marquette University, Milwaukee, WI, USA

Tampa Bay Rays Professional Baseball Team,
St. Petersburg, FL, USA
e-mail: kwilkpt@hotmail.com

Introduction

The rehabilitation program following anterior cruciate ligament (ACL) injury continues to evolve. In the 1980s, rehabilitation focused on protection using immobilization, guarded range of motion (ROM), strengthening exercises, a delayed return to function, and, finally, return to sports at approximately 12 months. In the 1990s, rehabilitation transitioned to immediate motion [53, 55], immediate weight bearing, functional exercises, and an emphasis on proprioception and neuromuscular control [44, 71], thus allowing an earlier return to functional activities. The term "accelerated rehabilitation" was frequently used. Currently, the focus of rehabilitation is to progress the patient at a more moderate rate than described in accelerated protocols. The emphasis is now on joint protection and knee joint longevity, with the primary goal being functional dynamic stability. Overall, the return to functional activities and sports following ACL surgery is more rapid today than in the 1980s, partly due to the shift in rehabilitation philosophy and improved surgical techniques.

One noteworthy change in the evaluation of rehabilitation following ACL injury is the greater

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_20,

emphasis on neuromuscular training. In this chapter, proprioception and neuromuscular control are defined based on current literature, and the implications of each following ACL injury and surgery are discussed. Techniques are described to restore neuromuscular control and functional dynamic stability following ACL injury and/or surgery.

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 [45]. Wilk [69] defined neuromuscular control as the afferent sensory recognition of joint position and the efferent response to that awareness. Neuromuscular control provides the functional component referred to as dynamic stabilization.

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 [41] and thus contribute to dynamic joint stability. Receptors in muscles contribute to muscle stiffness through either force feedback, which is altered by the GTO [36], or length feedback, which is mediated by the muscle spindle pathway which facilitates motor activity [47, 48].

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 hamstrings. 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 [40], 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 brain stem, or the cerebral cortex [10]. 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 brain stem, cerebellum, and cortical levels involves longer pathways and, thus, slower response times. Numerous studies [12, 26, 62] 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 brain stem and the cerebellum, these pathways may be important in providing dynamic knee stability [20].

ACL injuries may disrupt the complex interactions within the neuromuscular system, resulting in diminished proprioception and kinesthesia, abnormal patterns of muscle activity [14], and reduced dynamic joint stability [5, 7, 44]. An ACL injury to one knee may in addition affect the proprioception on the opposite lower extremity [35, 74] and decrease muscle strength in the opposite quadriceps muscle [27, 32, 39]. 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 clarification. 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 [62]. 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. [16]. 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 that provides dynamic stabilization.
- Motor responses depend on level of processing of afferent inputs within CNS. Processing may occur at spinal cord, brain stem, or cerebral cortex. Sensory input processed at CNS above spinal cord level may be altered with neuromuscular training.
- 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.

Effects of ACL Injury on Proprioception

Several investigations reported a decrease in proprioception and kinesthesia following ACL injury [5–8, 35]. After ACL injury, deafferentation of peripheral sensory receptors occurs [8, 63], causing rapid alterations in proprioception. Lephart and associates [45] reported that changes in proprioception may occur within 24 h of ACL injury. Alterations in proprioception may persist for 1–2 years after surgery [19, 76, 77].

Following an injury, changes occur within the joint that influence normal recruitment and timing patterns of the surrounding musculature [24]. 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. [58] 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 [74] 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. [7] applied 100 N of anterior shear force in ACL-deficient patients and reported a reflexive activation of the hamstring muscles occurred. Paterno et al. [59] 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 [35, 38, 59, 67, 74, 76, 77] have demonstrated differences exist between the

ACL-reconstructed and opposite limbs for an extended period of time following surgery.

Hooks et al. [35] 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 following that time period.

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 [1] and Berchuck et al. [9] 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.

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. [31] 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. [30] 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. [61] 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.

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 deafferentation 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" [71, 72]. It is important to control or minimize hyperpronation of the foot, thus controlling tibial internal rotation. Paterno et al. [60] 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.

Stages of Motor Skill Development

There are four stages of progressing when learning a new motor skill: mobility, stability, controlled mobility, and skill [66]. 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. [13] classified motor skill development into 3 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. For example, 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 training 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.

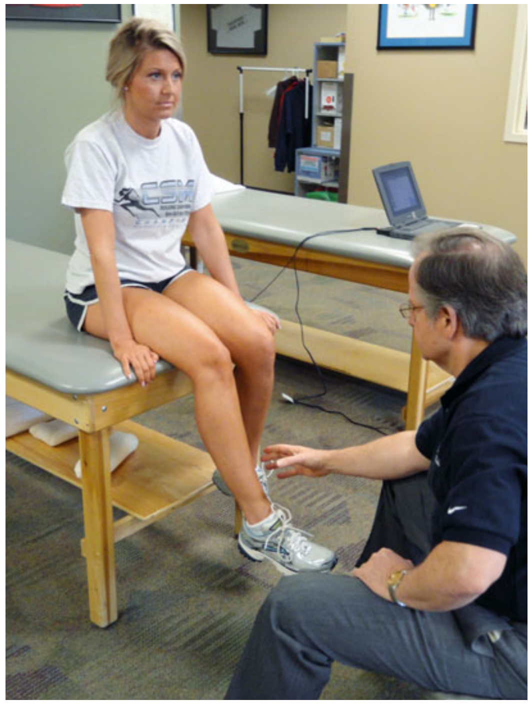


Fig. 20.1 Passive then active joint repositioning drill. The patient's lower extremity is placed at a measured range of motion by the clinician. The clinician then returns the lower extremity to the rest position and asks the patient to actively position the lower extremity in the same position that the clinician placed it in previously

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. 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 [21, 52]. 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. [22] 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 major bone bruising or articular cartilage damage are also not candidates for the early return 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 sports activities.

Joint Repositioning

Lephart et al. [44, 45] 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. 20.1). This technique

Fig. 20.2 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. 20.3 Balance training done on a force platform so that the patient receives visual feedback regarding the amount of weight distribution between the lower extremities

may be performed as either a test of proprioception or as a rehabilitation training technique following ACL injury or surgery.

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. 20.2) or on a force platform to determine the patient's weight distribution (Fig. 20.3). Available devices include wobble boards (Fig. 20.4), rocker boards (Fig. 20.5), and the Biodex Stability System (Biodex Medical Systems, Shirley, NY) (Fig. 20.2).

Fig. 20.4 Wobble board used for balance training drills

Fig. 20.5 Rocker boards used for balance training and perturbation training drills

Pertubation Training

Pertubation 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, 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. Pertubation 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. This exercise is progressed from single-plane to multi-plane challenges.

Wilk et al. [70] introduced perturbation training in the ACL-injured female athlete in 1996. Later, Wilk et al. [73] emphasized this form of training as a "critical component" for athletes to master to enable the successful return to athletic activities. Fitzgerald et al. [28] reported that perturbation training resulted in improved outcomes in ACL-deficient knee patients in regard to return to sports. Wilk and associates [68, 70, 72, 73] and Snyder-Mackler et al. [65] strongly recommended this form of training for ACL rehabilitation. In ACL-deficient knees, Chmielewski et al. [14, 16] reported that perturbation training enhanced the restoration of knee joint kinematics and a reduction in quadriceps-hamstring muscle co-activation. Hurd et al. [37] reported that perturbation training enhanced neuromuscular training and improved muscle activity and dynamic stability in female athletes.

Plyometric Exercises

Plyometrics is a term that commonly refers to jump training or stretch-shortening exercise drills. Wilk et al. [68] 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 [34, 42, 46] have shown that a well-designed plyometric program can reduce the incidence of ACL injuries in the female athlete (see Part IV).

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. [23] 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. [56] and Barber-Westin et al. [4] suggested using a video drop-jump test to detect a lower-limb valgus position on landing. Lower-extremity plyometrics are progressed from double-legged 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.

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 [33]. Technique training reduced the incidence of ACL injury in one study [51]. Proper technique during soccer-specific maneuvers described by Mandelbaum et al. [46] 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 [3, 33]. 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. [49] reported that plyometrics and balance training are effective in improving neuromuscular control. Myer et al. [50] reported that balance and plyometric training can reduce the valgus moment at the knee joint.

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. [18] 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. Chmielewski et al. [17] also reported interventions that increased self-efficacy or decreased fear of movement had 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, progressive in levels of difficulty, use both isolated 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.

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 3 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/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 program is reviewed with the patient so they are prepared for the operation.

The Postoperative Rehabilitation Program

The author's rehabilitation program following ACL bone-patellar tendon-bone autograft reconstruction is shown in Tables 20.1 and 20.2. 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 ten 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. Pertubation training to enhance neuromuscular control.
7. Train to improve endurance.
8. Challenge the neuromuscular system.
9. Gradually increase challenges to the neuromuscular system.
10. Neuromuscular training never stops; enhancement continues for years.

The four-phased neuromuscular training program is shown in Table 20.3. This chapter briefly discusses examples of drills in each phase of the rehabilitation program.

Phase I: Acute Phase Drills

A variety of neuromuscular training drills and activities may be initiated immediately following 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. 20.6). 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. 20.7 and 20.8). Electrical muscle stimulation (Emi Medical, St. Paul, Minnesota) to the

Table 20.1 Rehabilitation program following ACL bone-patellar tendon-bone autograft reconstructiona

Phase, postoperative day	Goals	Brace, weight bearing, range of motion	Exercises	Modalities	Neuromuscular, proprioception training
Phase 1	Restore full passive knee extension	Brace or immobilizer, knee locked in full extension during ambulation, sleeping; unlocked while sitting	Ankle pumps	EMS during active muscle exercises (4–6 h/day)	
Day 1	Diminish joint swelling, pain	2 crutches, weight bearing as tolerated	Overpressure into full, passive knee extension	Continuous passive motion as needed, 0–45°/50° (as tolerated, directed by physician)	
	Restore patellar mobility		Active, passive knee flexion (90° by day 5)	Ice 20 min every hour	
	Gradually improve knee flexion		Straight leg raises (flexion, abduction, adduction)	Elevate with knee in full extension	
	Reestablish quadriceps control		Quadriceps isometric setting		
	Restore independent ambulation		Hamstring stretches		
			Closed kinetic chain exercises: mini-squats, weight shifts		
Phase 1	Same	Brace or immobilizer, locked at 0° extension for ambulation, unlocked for sitting.	Multi-angle isometrics (90°, 60°)	EMS 6 h/day	
Days 2–3		2 crutches, weight bearing as tolerated.	Knee extension (90–40°)	Continuous passive motion as needed, 0–90°	
		ROM: remove brace, perform 4–6 × day	Overpressure into extension (knee extension at least 0° to slight hyperextension)	Ice 20 min every hour	
			Patellar mobilization	Elevate with knee in full extension	
			Ankle pumps		
			Straight leg raises (3 directions)		
			Mini-squats, weight shifts		
			Quadriceps isometric setting		
Phase 1	Same	Brace or immobilizer, locked at 0° extension for ambulation, unlocked for sitting.	Multi-angle isometrics (90°, 60°)	EMS 6 h/day	OKC passive-active joint repositioning 90°, 60°

(continued)

Table 20.1 (continued)

Phase, postoperative day	Goals	Brace, weight bearing, range of motion	Exercises	Modalities	Neuromuscular, proprioception training
Days 4–7		2 crutches, weight bearing as tolerated	Knee extension (90–40°)	Continuous passive motion as needed 0–90°	CKC squats, weight shifts with repositioning
		ROM: remove brace, perform 4–6 times/day, knee flexion 90° by day 5, 100° by day 7	Overpressure into extension (extension 0° to 5–7° hyperextension)	Ice 20 min every hour	
			Patellar mobilization (5–8 times daily)	Elevate with knee in full extension	
			Ankle pumps		
			Straight leg raises (3 directions)		
			Mini-squats, weight shifts		
			Standing hamstring curls		
			Quadriceps isometric setting		
Phase II	Maintain full passive knee extension (at least 0° to 5–7° hyperextension)	Continue locked brace for ambulation, sleeping	Muscle stimulation to quadriceps exercises	Swelling control – ice, compression, elevation	OKC passive-active joint repositioning 90°, 60°, 30°
Week 2	Gradually increase knee flexion	Weight bearing as tolerated (goal, discontinue crutches 10–14 days post-op)	Isometric quadriceps sets		CKC joint repositioning during squats and lunges
	Diminish swelling, pain	PROM: self-ROM stretching (4–5 times daily), emphasis on maintaining full PROM	Straight leg raises (4 planes)		Initiate squats on tiltboard
	Promote muscle control, activation		Leg press (0–60°)		
	Restore proprioception, neuromuscular control		Knee extension (90–40°)		
	Normalize patellar mobility		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 to 1 lb per week		

Phase II	Same	Discontinue locked brace (may use ROM brace for ambulation). If patient continues to use brace, unlock for ambulation	Continue all exercises from week 2	Same	Continue passive, active reposition drills (CKC, OKC)
Week 3		PROM: continue ROM stretching, overpressure into extension (ROM should be 0–100°/105°)	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		
Phase III	Restore full ROM (5–0–125°)	Brace – discontinue, may use knee sleeve to control swelling, add support	Progress isometric strengthening program		Tiltboard squats (perturbation)
Weeks 4–5	Improve lower-extremity strength	ROM: self-ROM (4–5 times daily using the other leg to provide ROM), emphasis on maintaining 0° passive extension	Leg press (0–100°)		Passive-active reposition OKC
	Enhance proprioception, balance, neuromuscular control	PROM 0–125°	Knee extension (90–40°)		CKC repositioning on tiltboard
	Improve muscular endurance		Hamstring curls (isotonics) Hip abduction-adduction Hip flexion-extension Lateral step-overs		
	Restore limb confidence, function		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		

(continued)

Table 20.1 (continued)

Phase, postoperative day	Goals	Brace, weight bearing, range of motion	Exercises	Modalities	Neuromuscular, proprioception training
Weeks 6–7	Same		Continue all exercises Pool running (forward), agility drills Balance on tiltboards 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 tiltboard
Week 10	Same		Continue all exercises from weeks 6, 8, 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 Tiltboard 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

ROM range of motion, *EMS* electrical muscle stimulation, *OKC* open kinetic chain, *CKC* closed kinetic chain, *PROM* passive range of motion
[a]See Table 22.2 for criteria to advance from one phase to the next

Table 20.2 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

Table 20.3 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)
	Tiltboard 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 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
	Side-lying clams
	Intrinsic foot exercise (towel gathering, marbles)
	Theraband inversion and eversion

(continued)

Table 20.3 (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 tiltboard (stabilize)
	Onto tiltboard with ball catch
	Tiltboard 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
	4 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, 4 corners
	Onto 1 box
	Onto 2 boxes
	Scissor jumps on floor
	Scissor jumps onto box
	Skip jumps
	Bounding drills
	Pertubation 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. 20.6 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. 20.8 Lateral cone walking done in the 3-repetition sequence used in the forward and backward cone walking drill

Fig. 20.7 Forward and backward cone walking. The patient is instructed to go through the cones 3 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

quadriceps (Fig. 20.9) 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 [64].

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. 20.10). Escamilla et al. [25] and Wilk et al. [70] 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

Fig. 20.9 Neuromuscular stimulation applied to the quadriceps to facilitate a muscular contraction

rubber band around the hip (Fig. 20.11). Stability and balance may be increased by performing squats on a Biodex Stability System (Fig. 20.2).

A compression sleeve (Bauerfeind USA, Atlanta, Georgia) is worn when the patient performs daily activities to improve the patient's joint awareness (Fig. 20.2b). Birmingham et al. [11] reported that wearing an elastic sleeve improved proprioception by 25 %.

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

Fig. 20.10 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

resistance cord first in a straight plane (Fig. 20.12), then in a diagonal plane (Fig. 20.13), and finally with rotation (Fig. 20.14). This drill may be progressed to landing on a unilateral surface such as foam (Fig. 20.15) or an air mattress (Fig 20.16). The goal is to land with the knee 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 [70].

Other drills include front step-downs (Fig. 20.17) 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. 20.18) to diminish the patient's conscious awareness of their knee joint. One study [15] reported that performance on the front step-down correlated to the patient's functional level and degree of satisfaction.

Fig. 20.11 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. 20.12 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. 20.13 SportCord lateral lunges performed in the diagonal plane

Fig. 20.14 SportCord lateral lunges performed with rotation

Fig. 20.15 SportCord lateral lunges performed onto an unstable surface, such as a piece of foam. The foam is used to create an unstable surface for landing so that the patient's proprioception is improved

Fig. 20.16 SportCord lateral lunges performed onto an air mattress to create an unstable landing surface

Fig. 20.17 The front step-down performed on a box. The ability to perform this exercise correlates with the patient's functional level

Squats on an unstable surface are excellent to perform in this phase, such as on a BOSU ball (Fitness Quest, Ashland, Ohio) (Fig. 20.19) 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 emphasized through a variety of exercise drills along with foot and ankle exercise drills.

Endurance exercises are gradually implemented. Numerous authors [43, 57, 75] have shown that once a joint is fatigued, proprioception is significantly decreased (in some cases, up to 75 %). Wojtys et al. [75] demonstrated a significantly slower response time in the quadriceps, hamstrings, and gastrocnemius post a fatiguing protocol.

Fig. 20.18 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 the thigh to activate the hip abductors

Fig. 20.19 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

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. 20.20) to single-leg holds at 30° flexion, to single-leg squats from 0° to 45° with holds, and to single-leg holds at 30° flexion with a ball throw and catch (Fig. 20.21). 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. 20.22) or a tiltboard 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. 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. 20.23) because it enhances both proprioception and coordination.

Phase IV: Functional and Skills 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 sports activities,

Fig. 20.20 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

Fig. 20.21 Single-leg balance holds on a tiltboard 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

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. 20.24), followed by two-box jumps (Fig. 20.25), 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 [29]. The patient progresses to side shuffles, cariocas, and then forward running. Once the patient demonstrates a normal gait pattern 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 [2, 54]. The specific criteria required to advance through the rehabilitation program phases are shown in Table 20.2.

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

Fig. 20.22 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. 20.23 The Monitored Rehab System (CDM Sport, Fort Worth, Texas) leg press or squat machine. The system combines proprioception and neuromuscular training with strength training

Fig. 20.24 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

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.

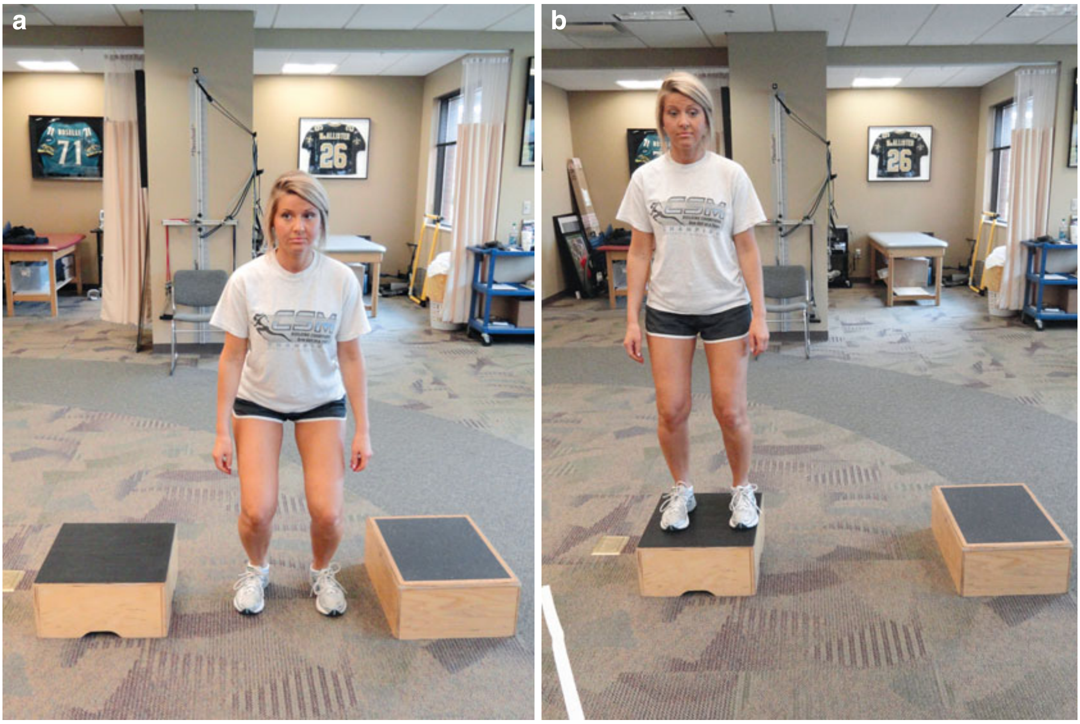


Fig. 20.25 Two-box plyometric jump exercise. The patient begins between two boxes on the floor. The patient jumps from the floor laterally to one box, back down to the floor, and then the opposite direction to the second box. The patient is instructed to land with "quiet feet" and to avoid a lower-limb valgus position

References

1. Andriacchi TP, Birac D (1993) Functional testing in the anterior cruciate ligament-deficient knee. Clin Orthop Relat Res 288:40–47
2. Barber SD, Noyes FR, Mangine RE et al (1990) Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. Clin Orthop 255:204–214
3. Barber-Westin SD, Noyes FR (2009) Decreasing the risk of anterior cruciate ligament injuries in female athletes. In: Noyes FR (ed) Noyes' Knee Disorders: surgery, rehabilitation. Clinical Outcomes, Saunders, Philadelphia, pp 428–463
4. Barber-Westin SD, Smith ST, Campbell T et al (2010) The drop-jump video screening test: retention of improvement in neuromuscular control in female volleyball players. J Strength Cond Res 24(11): 3055–3062
5. Barrack RL, Skinner HB, Buckley SL (1989) Proprioception in the anterior cruciate deficient knee. Am J Sports Med 17(1):1–6
6. Barrett DS, Cobb AG, Bentley G (1991) Joint proprioception in normal, osteoarthritic and replaced knees. J Bone Joint Surg Br 73(1):53–56
7. Beard DJ, Kyberd PJ, Fergusson CM (1993) Proprioception after rupture of the anterior cruciate ligament. An objective indication of the need for surgery? J Bone Joint Surg Br 75B(2):311–315
8. Beard DJ, Dodd CAF, Trundle HR et al (1994) Proprioception enhancement for anterior cruciate ligament deficiency. A prospective randomised trial of two physiotherapy regimes. J Bone Joint Surg Br 76B(4):654–659
9. Berchuck M, Andriacchi TP, Bach BR et al (1990) Gait adaptations by patients who have a deficient anterior cruciate ligament. J Bone Joint Surg Am 72(6):871–877
10. Biedert RM (2000) Contribution of the three levels of nervous system motor control: spinal cord, lower brain, cerebral cortex. In: Lephart S, Fu F (eds) Proprioception and neuromuscular control in joint stability. Human Kinetics, Champaign, pp 23–29
11. Birmingham TB, Kramer JF, Inglis JT et al (1998) Effect of a neoprene sleeve on knee joint position sense during sitting open kinetic chain and supine closed kinetic chain tests. Am J Sports Med 26(4):562–566
12. Brooks V (1986) The neural basis of motor control. Oxford University Press, New York
13. Chmielewski T, Hewett TE, Hurd WJ (2007) Principles of neuromuscular control for injury prevention and

rehabilitation. In: Magee D, Zachazewski JE, Quillen WS (eds) Scientific foundations and principles of practice in musculoskeletal rehabilitation, vol 2. Saunders, St. Louis, pp 375–387
14. Chmielewski TL, Rudolph KS, Snyder-Mackler L (2002) Development of dynamic knee stability after acute ACL injury. J Electromyogr Kinesiol 12(4):267–274
15. Chmielewski TL, Wilk KE, Snyder-Mackler L (2002) Changes in weight-bearing following injury or surgical reconstruction of the ACL: relationship to quadriceps strength and function. Gait Posture 16(1):87–95
16. Chmielewski TL, Hurd WJ, Rudolph KS (2005) Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. Phys Ther 85(8):740–749, discussion 750–744
17. Chmielewski TL, Jones D, Day T et al (2008) The association of pain and fear of movement/reinjury with function during anterior cruciate ligament reconstruction rehabilitation. J Orthop Sports Phys Ther 38(12):746–753
18. Chmielewski TL, Zeppieri G Jr, Lentz TA et al (2011) Longitudinal changes in psychosocial factors and their association with knee pain and function after anterior cruciate ligament reconstruction. Phys Ther 91(9):1355–1366
19. Denti M, Randelli P, Lo Vetere D (2000) Motor control performance in the lower extremity: normals vs. anterior cruciate ligament reconstructed knees 5–8 years from the index surgery. Knee Surg Sports Traumatol Arthrosc 8(5):296–300
20. Di Fabio RP, Graf B, Badke MB et al (1992) Effect of knee joint laxity on long-loop postural reflexes: evidence for a human capsular-hamstring reflex. Exp Brain Res 90(1):189–200
21. Diener HC, Horak FB, Nashner LM (1988) Influence of stimulus parameters on human postural responses. J Neurophysiol 59(6):1888–1905
22. Distefano LJ, Padua DA, Blackburn JT et al (2010) Integrated injury prevention program improves balance and vertical jump height in children. J Strength Cond Res 24(2):332–342
23. Durall CJ, Kernozek TW, Kersten M et al (2011) Associations between single-leg postural control and drop-landing mechanics in healthy women. J Sport Rehabil 20(4):406–418
24. Dutton M (2004) Neuromuscular control. In: Dutton M (ed) Orthopaedic examination, evaluation and intervention. McGraw Hill, New York, pp 55–57
25. Escamilla RF, Fleisig GS, Zheng N et al (1998) Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. Med Sci Sports Exerc 30(4):556–569
26. Evarts EV (1973) Motor cortex reflexes associated with learned movement. Science 179(72):501–503
27. Farquhar SJ, Chmielewski TL, Snyder-Mackler L (2005) Accuracy of predicting maximal quadriceps force from submaximal effort contractions after anterior cruciate ligament injury. Muscle Nerve 32(4): 500–505
28. Fitzgerald GK, Axe MJ, Snyder-Mackler L (2000) The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physical active individuals. Phys Ther 80(2):128–140
29. Flynn TW, Soutas-Little RW (1993) Mechanical power and muscle action during forward and backward running. J Orthop Sports Phys Ther 17(2):108–112
30. Fremerey RW, Lobenhoffer P, Zeichen J et al (2000) Proprioception after rehabilitation and reconstruction in knees with deficiency of the anterior cruciate ligament: a prospective, longitudinal study. J Bone Joint Surg Br 82(6):801–806
31. Harrison EL, Duenkel N, Dunlop R et al (1994) Evaluation of single-leg standing following anterior cruciate ligament surgery and rehabilitation. Phys Ther 74(3):245–252
32. Hart JM, Pietrosimone B, Hertel J et al (2010) Quadriceps activation following knee injuries: a systematic review. J Athl Train 45(1):87–97
33. Hewett TE, Stroupe AL, Nance TA et al (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24(6):765–773
34. Hewett TE, Lindenfeld TN, Riccobene JV et al (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27(6):699–706
35. Hooks TR, Wilk KE, Reinold MM (2003) Comparison of proprioceptive deficits of the involved and noninvolved lower extremity following ACL injury and surgical reconstruction. J Orthop Sports Phys Ther 33:A59
36. Houk J, Simon W (1967) Responses of Golgi tendon organs to forces applied to muscle tendon. J Neurophysiol 30(6):1466–1481
37. Hurd WJ, Chmielewski TL, Snyder-Mackler L (2006) Perturbation-enhanced neuromuscular training alters muscle activity in female athletes. Knee Surg Sports Traumatol Arthrosc 14(1):60–69
38. Hurd WJ, Axe MJ, Snyder-Mackler L (2008) A 10-year prospective trial of a patient management algorithm and screening examination for highly active individuals with anterior cruciate ligament injury: part 2, determinants of dynamic knee stability. Am J Sports Med 36(1):48–56
39. Hurley MV, Jones DW, Newham DJ (1994) Arthrogenic quadriceps inhibition and rehabilitation of patients with extensive traumatic knee injuries. Clin Sci (Lond) 86(3):305–310
40. Johansson H (1991) Role of knee ligaments in proprioception and regulation of muscle stiffness. J Electromyogr Kinesiol 1(3):158–179
41. Johansson H, Sjolander P, Sojka P (1991) Receptors in the knee joint ligaments and their role in the biomechanics of the joint. Crit Rev Biomed Eng 18(5):341–368
42. Labella CR, Huxford MR, Grissom J et al (2011) Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. Arch Pediatr Adolesc Med 165(11):1033–1040

43. Lattanzio PJ, Petrella RJ, Sproule JR et al (1997) Effects of fatigue on knee proprioception. Clin J Sport Med 7(1):22–27
44. Lephart S, Kocher MS, Fu F et al (1992) Proprioception following anterior cruciate ligament reconstruction. J Sport Rehabil 1:188–196
45. Lephart SM, Pincivero DM, Giraldo JL et al (1997) The role of proprioception in the management and rehabilitation of athletic injuries. Am J Sports Med 25(1):130–137
46. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010
47. Matthews PB (1971) Recent advances in the understanding of the muscle spindle. Sci Basis Med Annu Rev ISSN: 0080–7729, 99–128.
48. Matthews PB (1981) Evolving views on the internal operation and functional role of the muscle spindle. J Physiol 320:1–30
49. Myer GD, Ford KR, Brent JL (2006) The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. J Strength Cond Res 20(2):345–353
50. Myer GD, Ford KR, McLean SG et al (2006) The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. Am J Sports Med 34(3):445–455
51. Myklebust G, Engebretsen L, Braekken IH et al (2003) Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. Clin J Sport Med 13(2):71–78
52. Nashner LM, Shupert CL, Horak FB (1989) Organization of posture controls: an analysis of sensory and mechanical constraints. Prog Brain Res 80:411–418, discussion 395–417
53. Noyes FR, Mangine RE, Barber S (1987) Early knee motion after open and arthroscopic anterior cruciate ligament reconstruction. Am J Sports Med 15(2):149–160
54. Noyes FR, Barber SD, Mangine RE (1991) Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med 19(5):513–518
55. Noyes FR, Berrios-Torres S, Barber-Westin SD et al (2000) Prevention of permanent arthrofibrosis after anterior cruciate ligament reconstruction alone or combined with associated procedures: a prospective study in 443 knees. Knee Surg Sports Traumatol Arthrosc 8(4):196–206
56. 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
57. Nyland JA, Shapiro R, Stine RL et al (1994) Relationship of fatigued run and rapid stop to ground reaction forces, lower extremity kinematics, and muscle activation. J Orthop Sports Phys Ther 20(3):132–137
58. Palmieri-Smith RM, Kreinbrink J, Ashton-Miller JA et al (2007) Quadriceps inhibition induced by an experimental knee joint effusion affects knee joint mechanics during a single-legged drop landing. Am J Sports Med 35(8):1269–1275
59. Paterno MV, Ford KR, Myer GD et al (2007) Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. Clin J Sport Med 17(4):258–262
60. Paterno MV, Schmitt LC, Ford KR et al (2010) Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. Am J Sports Med 38(10):1968–1978
61. Roberts D, Andersson G, Friden T (2004) Knee joint proprioception in ACL-deficient knees is related to cartilage injury, laxity and age: a retrospective study of 54 patients. Acta Orthop Scand 75(1):78–83
62. Schmidt R, Lee T (1999) Motor control and learning: a behavioral emphasis, 3rd edn. Human Kinetics, Champaign
63. Skinner HB, Wyatt MP, Hodgdon JA et al (1986) Effect of fatigue on joint position sense of the knee. J Orthop Res 4(1):112–118
64. Snyder-Mackler L, Ladin Z, Schepsis AA et al (1991) Electrical stimulation of the thigh muscles after reconstruction of the anterior cruciate ligament. J Bone Joint Surg Am 73:1025–1036
65. Snyder-Mackler L, Delitto A, Bailey SL (1995) Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. A prospective, randomized clinical trial of electrical stimulation. J Bone Joint Surg Am 77A(8):1166–1173
66. Sullivan PE, Markos PD, Minor MA (1982) An integrated approach to therapeutic exercise, theory, and clinical application. Reston Pub. Co., Reston
67. Swanik CB, Lephart SM, Giraldo JL et al (1999) Reactive muscle firing of anterior cruciate ligament-injured females during functional activities. J Athl Train 34(2):121–129
68. Wilk KE, Voight ML, Keirns MA et al (1993) Stretch-shortening drills for the upper extremities: theory and clinical application. J Orthop Sports Phys Ther 17(5): 225–239
69. Wilk KE (1994) Rehabilitation of isolated and combined posterior cruciate ligament injuries. Clin Sports Med 13(3):649–677
70. Wilk KE, Escamilla RF, Fleisig GS et al (1996) A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. Am J Sports Med 24(4):518–527
71. Wilk KE, Arrigo C, Andrews JR et al (1999) Rehabilitation after anterior cruciate ligament reconstruction in the female athlete. J Athl Train 34(2): 177–193
72. Wilk KE, Reinold MM, Hooks TR (2003) Recent advances in the rehabilitation of isolated and combined anterior cruciate ligament injuries. Orthop Clin North Am 34(1):107–137

73. Wilk KE, Macrina LC, Cain EL et al (2012) Recent advances in the rehabilitation of anterior cruciate ligament injuries. J Orthop Sports Phys Ther 42(3):153–171
74. Wojtys EM, Huston LJ (1994) Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities. Am J Sports Med 22(1):89–104
75. Wojtys EM, Wylie BB, Huston LJ (1996) The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. Am J Sports Med 24(5):615–621
76. Yosmaoglu HB, Baltaci G, Kaya D et al (2011) Tracking ability, motor coordination, and functional determinants after anterior cruciate ligament reconstruction. J Sport Rehabil 20(2):207–218
77. Zouita Ben Moussa A, Zouita S, Dziri C et al (2009) Single-leg assessment of postural stability and knee functional outcome two years after anterior cruciate ligament reconstruction. Ann Phys Rehabil Med 52(6):475–484

Part VI

Future Directions

Promotion of ACL Intervention Training Worldwide

21

Sue D. Barber-Westin and Frank R. Noyes

Contents

Introduction

Prevention of sports medicine injuries has long been established as vital to athletes of all ages, skill levels, and motivations. In 1972, Emerson [10] stated, "the past 35 years have seen the emergence of an unprecedented interest in sports-related injuries" and recalled documented efforts to prevent or reduce injuries in high school and collegiate athletes in the early 1940s. In 1970, Haddon [24] presented ten strategies which were later described as a matrix [8] 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 on the treatment of injuries or damage to either people or property. Interestingly, most of Haddon's strategies are applicable to sports medicine injuries, including those to the anterior cruciate ligament (ACL) (Table 21.1).

In today's world, the need for continued work in identifying modifiable and non-modifiable risk factors for noncontact ACL injuries as discussed in Part III using multivariate models is evident [3, 42, 48, 49]. The development of an athletic profile using clinically feasible, cost-effective

S.D. Barber-Westin, B.S. (✉)
Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA
e-mail: sbwestin@csmref.org

F.R. Noyes, M.D.
Cincinnati Sportsmedicine and Orthopaedic Center, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

Cincinnati Sportsmedicine Research and Education Foundation, 10663 Montgomery Road, Cincinnati, Ohio 45242, USA

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_21, © Springer-Verlag Berlin Heidelberg 2012

Table 21.1 Haddon's ten strategies for reducing human and economic losses [24][a]

Strategy	Haddon's examples	Examples in relation to athletics and ACL injuries
Prevent the marshaling of the form of energy in the first place	Prevent generation of gunpowder, ionizing radiation, accumulation of snow where avalanches are possible	No participation in sports
Reduce the amount of energy marshaled	Reduce size of bombs, speed of vehicles	Reduce harmful moments and forces in the lower extremity
Prevent the release of the energy	Prevent discharge of nuclear devices, fall of elevators, "escape of tigers"	Prevent potentially deleterious movements such as landing with extended knees, cutting with foot far outside center of body's mass
Modify the rate or spatial distribution of release of the energy from its source	Slow burning rate of explosives, reduce slope of ski trails for beginners	Reduce ground reaction forces, increase hip and knee flexion angles, enhance earlier muscle activation to offset forces
Separate, in space or time, the energy being released from the susceptible structure, whether living or inanimate	Elimination of vehicles and their pathways from community areas used by children, placement of power lines out of reach	Not possible in sports
Separate, in space or time, the energy being release by interposition of a material barrier	Use safety glasses, shin guards, armor plates, shields	Prophylactic knee braces for medial collateral ligament tears, helmets for football and baseball
Modify appropriately the contact surface, subsurface, or basic structure that will come into contact with people	Eliminate, round, soften corners, edges, points that may injure people	Enhance shoe design, safer playing surfaces (natural and artificial), soft training surfaces for plyometrics
Strengthen the structure, living or nonliving, that might otherwise be damaged by the energy transfer	Toughen codes for structures built in earthquake, hurricane zones	Neuromuscular training, strength training, aerobic conditioning
Move rapidly in detection and evaluation of damage that has occurred or is occurring, and counter its continuation and extension	Building sprinkler systems, fire doors, firm alarms, emergency transportation	Fast and accurate diagnosis and immediate treatment of injury
After damage has occurred, use appropriate intermediate and long-term reparative and rehabilitative measures	May involve return to pre-event status or altered status	Rehabilitation and advanced training, testing to ensure athlete is able to safely return to sport

[a]While these strategies appear in logical order, the author indicated that no rank order or priority is assigned to the items on this list

methods [19] that would allow identification of individuals (both female and male) who are at increased risk for injury is paramount. 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 [39]. Programs that focus on neuromuscular retraining, strengthening, education, plyometrics, and dynamic balance can successfully improve biomechanical variables believed to contribute to ACL injury [26, 27, 41, 43]. With the well-known inherent problems that accompany ACL ruptures and potential for future premature osteoarthritis, the authors 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 become 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.

While 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 [11]. And, while some ACL programs have proven to be effective in reducing the injury rate, several interventions have had limited or no success which has been attributed to poor compliance, subject boredom, and inability of the program to achieve improvements in neuromuscular indices (see Chap. 18). There exists the need to conduct well-designed large-scale studies that can shed light on the ability of health care professionals to provide this intervention based on a public health approach [12, 13, 15, 17, 21, 48].

Critical Points

- Development of profile using clinically feasible, cost-effective methods that identify individuals at increased risk for ACL injury paramount
- Authors believe widespread implementation of ACL intervention programs indicated
- Few implementation studies done to date to assess the impact of ACL interventions in a real-world, uncontrolled setting
- Well-designed, large-scale studies required to determine the ability of health care professionals to provide intervention programs based on a public health approach

A Public Health Approach to ACL Intervention Programs

Background

Recently, authors have recommended that a public health approach be adopted for ACL injury risk screening and intervention training [48]. 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. 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 [31, 48]. As well, athletes may suffer psychological changes (anger, depression, loss of confidence) following ACL injury and reconstruction [6, 32, 37, 40, 52]. 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 treatment is substantial, averaging $12,740 US dollars per injury for ACL reconstruction [34] which does not include postoperative rehabilitation, braces, crutches, cold therapy machines, or future expenses which are expected due to the high prevalence of premature osteoarthritis. All of these problems qualify ACL injuries to be 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. 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.

Historically, general injury prevention models developed from the hypothesis advanced by Gordon in 1949 [22] that epidemiological principles used to prevent disease could also be applied to automobile accidents and injuries. Haddon expanded on this principle in developing his injury prevention matrix previously mentioned [24, 25]. In 1999, two other general injury prevention public health models were published by Cohen and Swift [8] and Glasgow et al. [21]. Glasgow et al. [21] discussed problems with highly controlled interventions that are intensive, expensive, and demanding for both the subject and provider. Unfortunately, these types of studies do not address how well an intervention will fair in the world of busy and cost-conscious public health and community centers.

The first injury prevention model designed specifically for sports was described by van Mechelen et al. [53] in 1992. This was followed by a framework published in 2006 by Finch [11] 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. [54] and Finch and Donaldson [12] contributed additional models for consideration, as discussed in section "Injury Prevention Outcome Models."

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 [36, 50]. To date, BSSTM have not been routinely used in the development or measurement of sports injury prevention research interventions [36]. McGlashan and Finch [36] 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 [1, 2], and the diffusion of innovation theory [45] in future sports injury prevention research is well indicated.

Injury Prevention Outcome Models

van Mechelen's Sequence of Prevention

In an effort to study intervention programs for sports injuries using epidemiological research methods, van Mechelen et al. [53] described a four-stage model or process termed the "sequence of prevention":

1. Establish the extent of the injury problem by describing the incidence and severity of the injury
2. Identify the factors and mechanisms responsible for the injury

3. Introduce preventive measures to reduce the future risk and/or severity of the injury, based on the etiological factors and the mechanism previously identified
4. Evaluate the effect of the preventive measure by repeating step #1

This publication represented a unique translation of a standard public health prevention model to the science of sports injuries. While this original model served as a valuable tool to guide further sports injury research efforts, there are numerous problems which limit its effectiveness [11]. One of the most problematic is the lack of assessment of implementation issues of the intervention into large numbers of participants or different settings. In addition, there is no method to determine the compliance and behaviors of participants. The intervention itself is considered to be effective only if the incidence of injury is reduced, without regard for other factors such as changes in athletic performance indicators and the efficiency of the program as determined by financial, practical, and administrative factors.

TRIPP Framework

The translating research into injury prevention practice (TRIPP) was developed next as a sports injury research framework [11]. Proposed by Finch [11] as an improvement on the van Mechelen model, this framework is directed toward understanding the implementation aspect of sports injury prevention, as well as building an evidence base for the program's effectiveness. 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

Finch 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.

Van Tiggelen Model

In 2008, Van Tiggelen et al. [54] proposed an expansion of the models of van Mechelen et al. [53] and Finch [11] in order to account for risk-taking behavior and compliance of the individual athlete (Fig. 21.1). 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 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. Second, the compliance and risk-taking behavior of the individual athlete is determined for the intervention. Regardless of the potential benefits of an intervention, its success relies on good compliance of the athlete. In addition, retention of the new techniques and processes is crucial for long-term injury risk reduction.

According to Lund and Aaro [35], 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, he or she may still not wish to undergo an intervention to lessen this risk. This is especially true if his or her peers and coach do not believe that the intervention will be effective. Van Tiggelen et al. [54] noted that the most appropriate way of

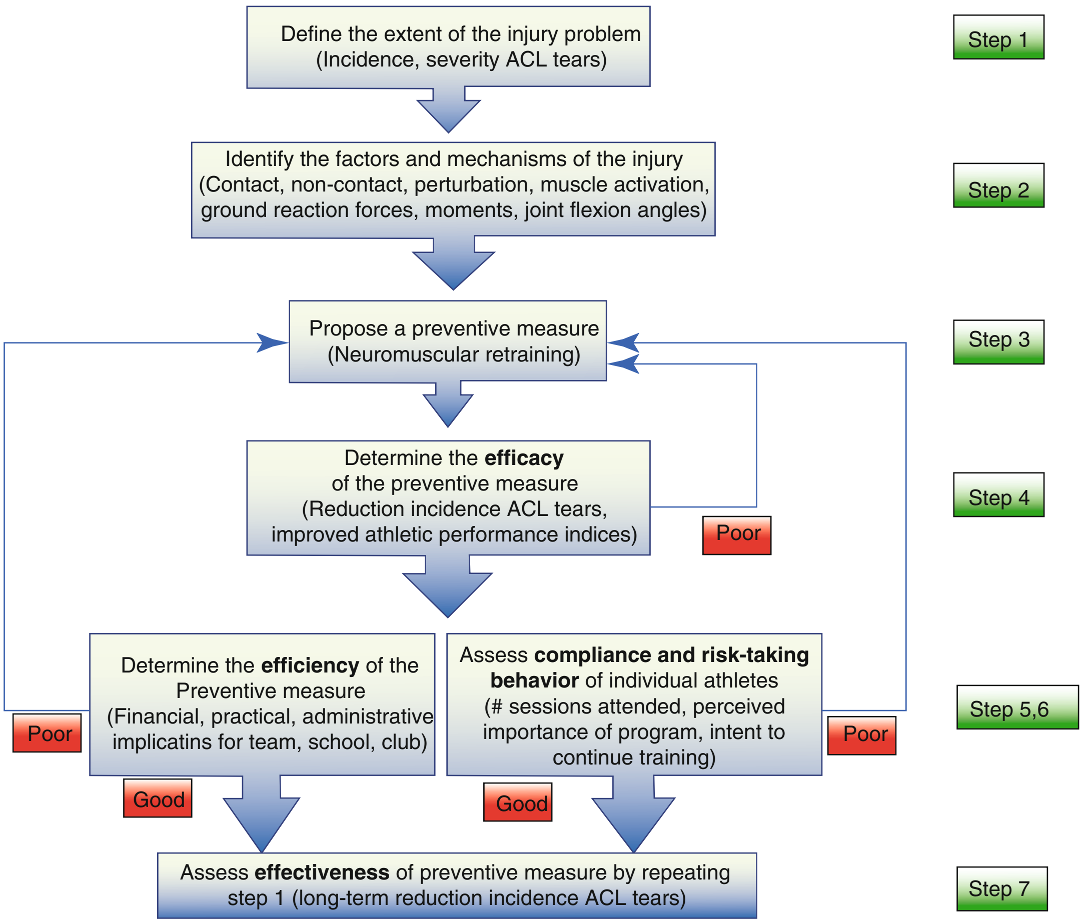


Fig. 21.1 Sequence of prevention of overuse injuries proposed by Van Tiggelen et al., with ACL injury intervention used as an example

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.

RE-AIM Framework

Glasgow et al. [21] described the problems of using findings from rigorous, intensive interventions tested in highly motivated subjects under controlled conditions as a basis for widespread implementation of an injury prevention program. The ability to recreate the intervention as intended by the program developers in uncontrolled circumstances with limited staff and resources, and unmotivated subjects, may not be possible. In order to study the ability of an intervention to indeed be effective in public health settings, these authors developed the RE-AIM model. This model measures the impact of an intervention by rating variables in five categories (Table 21.2):

- Reach
- Efficacy
- Adoption
- Implementation
- Maintenance

Each category may be comprised of a single question or a series of questions, based on the study. In general terms, reach is a measure of participation of a defined population. The authors stressed the importance of understanding the

Table 21.2 The RE-AIM model evaluation dimensions [21]

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 21.3 Use of the RE-AIM model to evaluate a tai chi program to prevent falls in the elderly [33]

Category	Variables measured	Results
Reach	No. of eligible subjects who responded to the program promotion (6 senior centers in 5 cities) × 100. Participant demographic characteristics compared to all users of senior centers	Reach = 87 % Participation eligible subjects = 89 % No difference demographics subjects who participated and other users of senior centers
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, $P < .001$
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 %

degree to which a program is able to reach those in need, because even small differences in risk levels between participants and non-participants may have a significant impact on cost-effectiveness and health. Measuring efficacy involves assessment of both positive and negative outcomes of a program. Adoption refers to the proportion of a population and caregivers that will use or try out a program. Implementation measures the extent to which a program is delivered as intended. Maintenance is 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 [33] and exercise programs for arthritis [23]. Table 21.3 shows the variables that were measured in the model's categories and results for the tai chi program investigation [33]. In addition to these variables, exist interviews were conducted in the 105 participants who completed the intervention which provided further insight into their opinion of the program and its benefits. All participants enjoyed the program, intended to continue practicing, and recommended it to others. The use of the RE-AIM model allowed recommendation of this program based on the achievement of high scores in all of the categories.

The RE-AIM model will be used in a future study to measure the outcomes of a lower limb injury prevention program in community Australian football [14]. In addition, this framework will evaluate an

Table 21.4 The RE-AIM Sports Setting Matrix (RE-AIM SSM): evaluation dimensions for community sport injury intervention delivery [12]

	Level of assessment/intervention setting or target					
RE-AIM dimension	National sport organization	State sport organization	Regional or league	Club	Team	Participant
Reach						
Effectiveness						
Adoption						
Implementation						
Maintenance						

This table shows all possible intervention points possible. The relevance of each point will depend on the nature and target of each intervention

injury prevention program recently developed for physical education classes of primary school children in the Netherlands [9].

RE-AIM SSM Framework

Finch and Donaldson [12] recently presented an extension of the RE-AIM model as a proposed method of evaluating sports injury intervention programs. This extended model identifies where each of the RE-AIM dimensions may be assessed across the sports delivery hierarchy (Table 21.4). This includes national organizations (such as the National Collegiate Athletic Association), state organizations, regional organizations or 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. An example was provided of how the RE-AIM SSM model could be used to evaluate the implementation and outcome of a lower extremity injury prevention program led by coaches in a community sports setting. Table 21.5 demonstrates potential variables that could be assessed for the RE-AIM categories of reach and effectiveness in the sports delivery hierarchy.

In order to continue to understand the complexities involved with implementation of sports injury prevention programs on a widespread basis, Finch and Donaldson [12] also proposed that these types of questions should be asked:

- What are the actual behaviors of the participants (high-risk vs. 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?

The Spectrum of Prevention Framework

Cohen and Swift [8] combined their injury prevention concepts with the Haddon matrix [24] and presented the "spectrum of prevention." This framework provides multiple approaches to developing and promoting injury prevention. Comprised of 6 levels of increasing scope, this tool progresses from enhancing individual knowledge to influencing local, state, and national policy and legislation:

1. Strengthening individual knowledge and skills
2. Promoting community education
3. Educating providers
4. Fostering coalitions and networks

Table 21.5 Proposed application of the RE-AIM model to evaluate the implementation of a community-based, coach-led lower limb injury prevention program [12][a]

RE-AIM category	Level assessment/intervention	Variables measured
Reach	National sports organization	% Administrators aware of program
		% Administrators think program is a good idea
	State sports organization	% Administrators aware of program
		% Administrators think program is a good idea
	Association/league	% Participating in program
		% Offering education/promotion about the program
	Club	% Aware of program
	Team	% Coaches aware of program
		% Coaches attending education classes about program
	Participant	% Exposed to program via coaches
Effectiveness	National sports organization	% Reduction in injuries in associations/leagues that implemented program compared to controls in other associations/leagues affiliated with national organization
	State sports organization	% Reduction in injuries in associations/leagues that implemented program compared to controls in other associations/leagues affiliated with state organization
	Association/league	% Reduction in injuries in clubs that implemented program compared to other clubs affiliated with association/league
	Club	% Reduction in injuries in club compared with other seasons
		% Clubs believe program reduces injury risk
		% Clubs believe program has other benefits (technique, performance)
	Team	% Coaches believe program reduces injury risk
		% Coaches believe program has other benefits (technique, performance)
	Participant	% Reduction injury rates compared to previous seasons
		% Able to perform program exercises correctly

[a]For the other three RE-AIM categories in this table, see reference [12]

5. Changing organizational practices
6. Influencing policy and legislation

The authors believe that, by using the Haddon matrix and their approach, health providers can devise multifaceted interventions that simultaneously address the issues highlighted by Haddon (multiple strategies to be used before, during, and after an injury). As well, the issues of influencing policy and legislation are included. The tool assists practitioners to go beyond what is usually a primarily education approach to develop wide-based networks that can achieve actual changes in policy and procedures. This framework has been used in a variety of disciplines, such as the World Health Organization, National Highway Traffic Safety Administration, and injury prevention projects in California.

Behavioral and Social Theories and Models

The Health Belief Model

The Health Belief Model (HBM) was developed in the early 1950s by social psychologists at the United States 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" [46]. 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 [16]. This represents the only study published to date to use these two models to assist in the design of a sports injury prevention delivery plan that would hopefully ensure maximum player participation in a future randomized controlled trial. The results of the survey are discussed in section "Coaches' Perspectives on Lower-Limb Injury Intervention Programs."

Theory of Planned Behavior

The Theory of Planned Behavior [1, 2, 38] model is based on the premise that a person's intention to perform a behavior is based on his/her attitude toward the behavior and the influence or control of the social environment (such as a peer group). This model represents an extension of the theory of reasoned action [18] by including the concept of perceived behavioral control (Fig. 21.2). The developers of the theory of planned behavior suggested that the previous theory of reasoned action, which relies on a person's attitude, subjective norms (belief that peer group thinks the person should or should not perform the behavior), and intention as the predictors of behavior, is insufficient whenever control over the behavioral goal is incomplete. This may happen because of internal factors such as skills, abilities, and knowledge or because of external factors such as time and opportunity. The theory of planned behavior encompasses the concepts of perceived behavioral control in which behaviors are influenced by second-hand information about the behavior, by the experiences of a person's social group, and by other factors. Therefore, performance of a behavior depends on both motivation and adequate control over the behavior. The addition of perceived behavior control improved the predictive ability of the model.

The theory of planned behavior was shown by Mummery et al. [38] to have a large contribution in predicting physical activity intention in a group of 677 school children from Canada. This study found that when a child held a positive attitude toward physical activity, perceived that others believed he or she should participate in physical activities, and felt that he or she had the ability to participate, that individual formed a strong intention to indeed participate.

Diffusion of Innovation Theory

Introduced in 1995, the Diffusion of Innovation Theory advances the hypothesis that, for people to adopt and use a new innovation or intervention, they will progress through five stages:

1. Gaining knowledge about the innovation
2. Forming positive attitudes about adopting the innovation
3. Deciding to adopt the innovation
4. Using the innovation
5. Confirming that the innovation is useful

The diffusion of innovation theory has been used in marketing, public health, communication, geography, sociology, and economics [4]. To date, two sports injury intervention studies have used this theory to determine the impact of the use of helmets at ski areas [4] and of the intentions of coaches to use a concussion prevention toolkit in high schools.

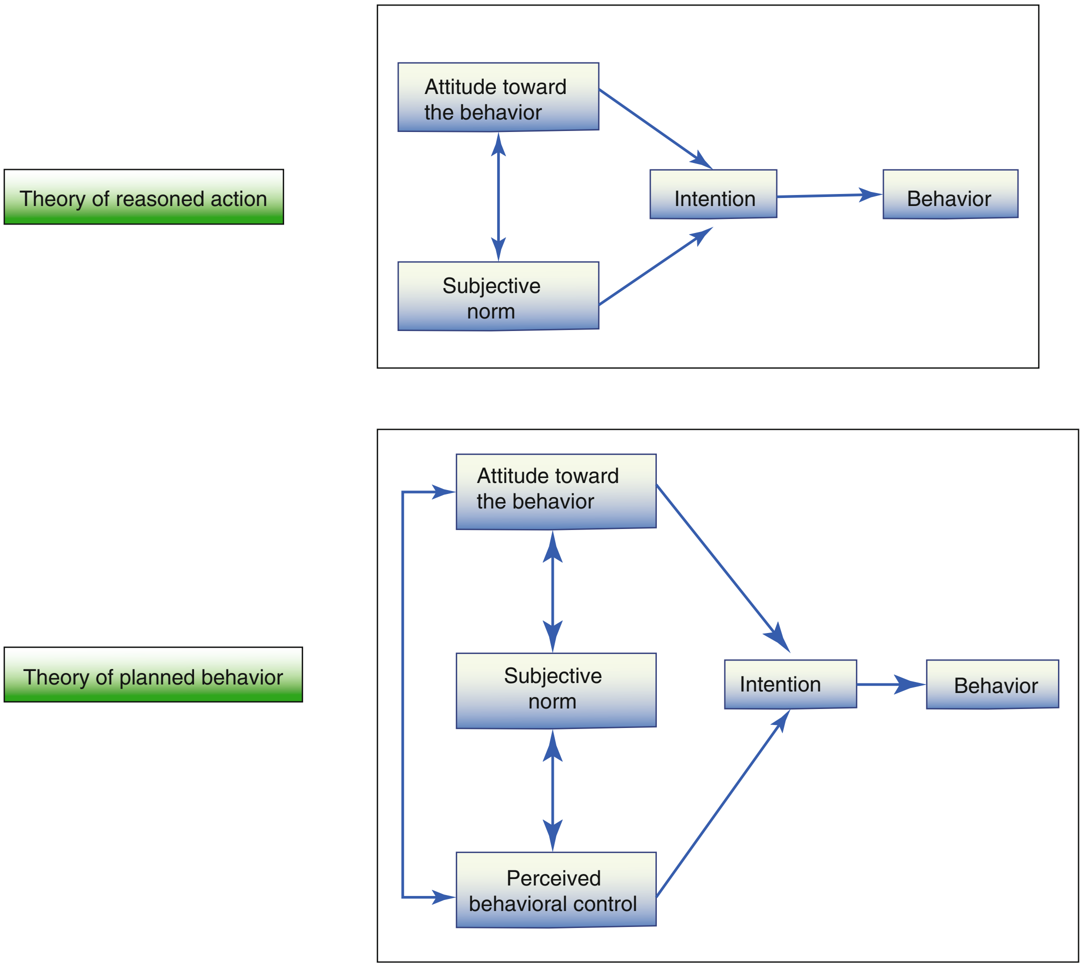


Fig. 21.2 Theory of reasoned action and theory of planned behavior

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:
  - van Mechelen's sequence of prevention: unique translation of a standard public health prevention model to the science of sports injuries
  - Translating research into injury prevention practice (TRIPP)
  - Van Tiggelen model
  - RE-AIM framework: reach, efficacy, adoption, implementation, and maintenance
  - RE-AIM SSM framework: assesses model across sports delivery hierarchy
  - Spectrum of prevention framework: progresses from enhancing individual knowledge to influencing local, state, national policy, and legislation

- Behavioral and social theories and models:
  – Health Belief Model beneficial to study beliefs and attitudes of athletes and coaches regarding injury risks and intervention training
  – Theory of Planned Behavior useful in predicting intent to perform a behavior

Knowledge and Attitudes of Athletes and 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. 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 [7, 51]. Research has demonstrated that behavior change interventions for children and adolescents are more effective when adult role models are involved [29]. Unfortunately, insufficient training of coaches and poor teaching techniques are associated with higher injury rates [5, 28]. 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.

Coaches' Perspectives on Lower Limb Injury Intervention Programs

Saunders et al. [47] 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 21.6). 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 (Table 21.7). 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.

In a separate study, the knowledge, attitudes, and beliefs of coaches involved with elite-level Australian football to lower limb sports injury prevention were assessed [51]. The purpose was

Table 21.6 Application of the RE-AIM framework in the evaluation of a coach-lead lower limb injury prevention training program in junior netball players [47]

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
	Percent of coaches providing constructive feedback on program	77 %
Maintenance	Percent of coaches who intend to use program with players in the future	88 %

Table 21.7 Coaches' views of the advantages and difficulties of a coach-lead lower limb injury prevention training program in junior netball players [47]

Responses to questions	%
Advantages of program	
Players improved other athletic indices	83
Reduced risk of injury	79
Players learned correct landing techniques	79
Improved ability to avoid stepping rule violations	63
Players improved other game skills	50
Difficulties with program	
Coach-related factors	
Ideas for training drills	79
Skills/not properly trained in this aspect of coaching	42
Time for training	63
Coaching skills	36
Training space	33
Training equipment	21
Player-related factors	
Not listening, not motivated	83
Older players did not believe they needed this type of training	71
Players not attending training regularly	71
Training drills too boring	46

to determine if information from research findings was translated into team practices. Each coach of the Premier Division from all nine clubs of the Sydney Australian Football League participated in a survey. As well, two training sessions were observed for each club to assess the duration and elements that comprised a typical practice session. The results clearly demonstrated that the coaches were unaware of the major elements of lower limb prevention training such as jump/landing training, changing direction/sidestepping, balance training, and weight/resistance training. This was true even though all of the coaches believed it was important for both the coach and player to have current knowledge regarding lower limb injury prevention strategies. The coaches ranked the need for injury prevention lower than general training sessions and team performance. The authors concluded that there was a "gap in the translation of research findings into sporting practice." However, it was encouraging to note that all coaches believed lower limb injury prevention was important to include in training sessions and that all would implement this type of training if it was proven to both reduce the incidence of injuries and improve player performance.

Table 21.8 Sample questions from the knowledge, attitudes, and practices questionnaire [29]

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

Finch et al. [16] surveyed the players of the coaches of the elite-level Australian football clubs described above to determine their beliefs and attitudes regarding lower limb injury risk factors and the value of intervention training. A survey composed of 24 questions was devised, whose theoretical basis was taken from the HBM and RE-AIM frameworks. The authors reported that 74 % of the players believed that doing specific exercises during training would reduce their risk of injury; however, 64 % felt that training should focus more on improving game performance than injury prevention. In a manner similar to that found for their coaches, the players were for the most part unaware of the role of jumping/landing techniques and balance training for injury prevention. The best approach for intervention appeared to be the implementation of exercises into regular practices. The authors hypothesized that conducting this model-based survey before the initiation of a randomized controlled trial of a lower limb injury prevention program would result in a study with "more rigor" than others previously conducted. This was because implementation issues of barriers, players' beliefs and attitudes, and facilitators to sustainable programs were measured.

Knowledge, Attitudes, and Beliefs of Players and Coaches Toward ACL Prevention Programs

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 [29]. In this investigation, the theory of planned behavior model was used to explain the relationship among coach and player factors in ACL injury prevention. The players and coaches 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 21.8). 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 21.9). Coaches who scored higher on the ACL knowledge scale had more favorable attitudes toward ACL injury prevention training (Table 21.10). Their players also scored higher on the postseason assessment. 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 is lacking regarding the role of the ACL and injury prevention techniques, despite the influence of media on the topic.

Gender Differences in High School Coaching Techniques and Attitudes

It is important to understand that gender differences appear to exist at the high school level in coaching techniques and attitudes [44]. A recent survey of 32 varsity high school coaches in one

Table 21.9 ACL knowledge, attitudes toward intervention training, and practice of intervention training in high school coaches and players [29]

Participants	Knowledge scale (mean points)	Attitude scale (mean points)	Practice scale (mean points)
Coaches, $n = 12$	68.8	85.6	61.1
Players preseason (before intervention), $n = 74$	57.3	73.5	58.4
Players postseason (after intervention), $n = 74$	61.8[a]	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

[a] $P < .01$ compared to preseason

Table 21.10 Changes in high school basketball players' knowledge, attitudes, and practices by school compared to baseline scores and coaches' baseline scores [29]

Scale	School #	Coach baseline score (mean points)	Player baseline score (mean points)	Change in player score (mean points)
Knowledge	1	68.75	58.3	9.0
	2	68.75	53.2	10.1
	3	75.0	66.0	1.4
	4	56.0	49.3	−0.01
	5	72.0	59.4	1.25
Attitude	1	98.1	73.5	7.0
	2	78.0	69.8	5.4
	3	76.0	80.2	1.85
	4	75.0	68.2	−5.0
	5	80.5	73.8	7.5
Practice	1	72.0	60.9	5.1
	2	63.5	66.4	2.0
	3	78.0	54.3	0.5
	4	60.0	60.2	−1.6
	5	64.5	60.2	−0.4

Scale scores, 0–100 points

state in the USA (Idaho) found many gender differences in regard to who designed and implemented strength and conditioning programs, whether or not the programs were provided or required, and how often training was conducted. The coaches were involved in soccer, basketball, baseball, and softball. For instance, 50 % of coaches of male athletes required their athletes to complete training compared with only 9 % of coaches of female athletes. In addition, 50 % of coaches of male athletes required training year round compared with only 17 % of coaches of female athletes. Coaches of female athletes were less likely to know the credentials of their strength coaches and less likely to be certified (Table 21.11). The authors concluded these attitudinal differences may reflect the low priority placed on strength training among coaches of female athletes.

Effectiveness of Coach Education and Resource Materials for Implementation of Injury Prevention Training

With coaches assuming a major role in conducting injury prevention training, the question arises of how to effectively educate them on the rationale and techniques to use to alter player's movement

Table 21.11 Current practices and gender differences in strength and conditioning programs in US high schools[a] [44]

Variable	% for female athletes	% for male athletes
Individuals who design and implement strength/conditioning programs[b]		
Physical education teacher	64	29
Head coach (self)	0	50
Other (other coach, staff, certified professional)	36	21
Educational background of strength/conditioning professional[b]		
Bachelors, masters, doctoral degree in physical education or related field	60	57
Unrelated bachelors, masters, doctoral degree	0	36
Unsure	40	7
Certifications held by strength/conditioning professional[b]		
Certified	20	47
Not certified	10	37
Unsure	70	16
Years of experience		
Highly experienced (>8 years)	40	50
Experienced (4–7 years)	10	29
Less experienced (0–3 years)	0	14
Unsure	50	7

[a]Data collected from surveys of 31 head coaches for basketball, soccer, and baseball/softball
[b]$P < .05$

patterns and neuromuscular indices to reduce the incidence of ACL injuries. There exists little information in the literature on the effectiveness of coach education in regard to injury prevention knowledge or training techniques. Few data are available that show how coaches apply information they receive in formal training programs and workshops to their practices and teaching techniques.

In 2010, Gianotti et al. [20] conducted a study to determine the efficacy of integrating sports injury prevention information into a coach education program. Coaches involved with soccer and netball in New Zealand attended workshops conducted by the national Accident Compensation Corporation (ACC) in association with Netball New Zealand and New Zealand Football. These agencies devised formal courses along with written resources (booklet and wallet card) in an effort to reduce injuries in these sports. Then, telephone interviews were conducted 4–12 months later to determine the impact of the education program and materials on coach knowledge and training techniques.

The results of the study, while limited by the percent of responses received in the follow-up interviews, showed encouraging data in terms of the viability of coach education for the delivery of injury prevention. For instance, 89 % of the netball coaches changed the way they coached, with 95 % using knowledge from the course and passing it on to players. Fortunately, in New Zealand, an infrastructure already existed in terms of a national organization which had the financial resources and incentive required for the resource materials. The authors pointed out that "having a model is not enough for community sport," but there must be a clear implementation plan, including funding, for such a program to exist and be beneficial. An analysis of the impact of sport injury prevention programs on ACC claims and costs was reported in a prior study [19]. A pre- and post-implementation cost-outcome formula for injury prevention was established for national community sports in 2003. This approach allows continued monitoring of costs for sports injury claims and for the ACC to manage expectations of the prevention programs, including when they will provide a return on investment. Long-term planning may then be accomplished for investment in sports injury prevention programs.

Critical Points

- Coaches frequently responsible for development and implementation of training programs; qualifications and knowledge important in influencing injury risk.
- RE-AIM model successfully used in coach-implemented netball injury intervention study:
  - Reach 50 %
  - Effectiveness, 79–88 %
- Elite-level Australian football coaches unaware major elements of lower limb injury prevention training.
- Theory of planned behavior: person's intention to perform a behavior based on attitude toward the behavior and the influence of the social environment:
  - Coaches' knowledge about ACL injuries, attitude toward intervention training influences players' knowledge and attitudes
- Gender differences exist at high school level in coaching techniques and attitudes:
  - Year-round training required 50 % coaches male athletes, 17 % coaches female athletes
- Few data available regarding effectiveness of coach education programs.

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, the authors developed a formal education program. The 11-h course promotes the widespread dissemination of the scientific basis and accurate knowledge on the function of the ACL, injury mechanisms, 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 ACL injuries
- Gender differences ACL injury rates and 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 and 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, described in Chap. 13. 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, and 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 1,300 trainers have attended this course from the United States and abroad including Austria, Brazil, Canada, Iceland, the United Kingdom, Japan, Qatar, and the Netherlands. It is postulated 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.

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 [42, 48]. 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.

References

1. Ajzen I, Fishbein M (1980) Understanding attitudes and predicting social behavior. Prentice-Hall, Englewood Cliffs
2. Ajzen I, Madden TJ (1986) Prediction of goal-directed behavior: attitudes, intentions, and perceived behavioral control. J Exp Soc Psychol 22:453–474
3. Ali N, Rouhi G (2010) Barriers to predicting the mechanisms and risk factors of non-contact anterior cruciate ligament injury. Open Biomed Eng J 4:178–189
4. Andersen PA, Buller DB, Scott MD et al (2004) Prevalence and diffusion of helmet use at ski areas in Western North America in 2001–02. Inj Prev 10(6): 358–362
5. Beck JL, Wildermuth BP (1985) The female athlete's knee. Clin Sports Med 4(2):345–366
6. Brand E, Nyland J (2009) Patient outcomes following anterior cruciate ligament reconstruction: the influence of psychological factors. Orthopedics 32(5):335
7. Chalmers DJ, Simpson JC, Depree R (2004) Tackling Rugby injury: lessons learned from the implementation of a five-year sports injury prevention program. J Sci Med Sport 7(1):74–84
8. Cohen L, Swift S (1999) The spectrum of prevention: developing a comprehensive approach to injury prevention. Inj Prev 5(3):203–207
9. Collard DC, Chinapaw MJ, van Mechelen W et al (2009) Design of the iPlay study: systematic development of a physical activity injury prevention programme for primary school children. Sports Med 39(11):889–901
10. Emerson RS (1972) The expanding frontiers of sports medicine. J Sports Med 1(1):36
11. Finch C (2006) A new framework for research leading to sports injury prevention. J Sci Med Sport 9(1–2):3–9; discussion 10
12. Finch CF, Donaldson A (2010) A sports setting matrix for understanding the implementation context for community sport. Br J Sports Med 44(13):973–978
13. Finch CF (2011) No longer lost in translation: the art and science of sports injury prevention implementation research. Br J Sports Med 45(16):1253–1257
14. Finch CF, Gabbe BJ, Lloyd DG et al (2011) Towards a national sports safety strategy: addressing facilitators and barriers towards safety guideline uptake. Inj Prev 17(3):e4
15. Finch CF, Ullah S, McIntosh AS (2011) Combining epidemiology and biomechanics in sports injury prevention research: a new approach for selecting suitable controls. Sports Med 41(1):59–72
16. Finch CF, White P, Twomey D et al (2011) Implementing an exercise-training programme to prevent lower-limb injuries: considerations for the development of a randomised controlled trial intervention delivery plan. Br J Sports Med 45(10):791–796
17. Finch CF (2012) Getting sports injury prevention on to public health agendas – addressing the shortfalls in current information sources. Br J Sports Med 46(1):70–74
18. Fishbein M, Ajzen I (1975) Belief, attitude, intention, and behavior: an introduction to theory and research. Addison-Wesley, Reading
19. Gianotti S, Hume PA (2007) A cost-outcome approach to pre and post-implementation of national sports injury prevention programmes. J Sci Med Sport 10(6): 436–446
20. Gianotti S, Hume PA, Tunstall H (2010) Efficacy of injury prevention related coach education within netball and soccer. J Sci Med Sport 13(1):32–35
21. Glasgow RE, Vogt TM, Boles SM (1999) Evaluating the public health impact of health promotion interventions: the RE-AIM framework. Am J Public Health 89(9):1322–1327
22. Gordon JE (1949) The epidemiology of accidents. Am J Public Health Nations Health 39(4):504–515
23. Gyurcsik NC, Brittain DR (2006) Partial examination of the public health impact of the people with arthritis can exercise (PACE) program: reach, adoption, and maintenance. Public Health Nurs 23(6):516–522
24. Haddon W Jr (1970) On the escape of tigers: an ecologic note. Am J Public Health Nations Health 60(12): 2229–2234
25. Haddon W Jr (1972) A logical framework for categorizing highway safety phenomena and activity. J Trauma 12(3):193–207
26. Herman DC, Onate JA, Weinhold PS et al (2009) The effects of feedback with and without strength training on lower extremity biomechanics. Am J Sports Med 37(7):1301–1308
27. Hewett TE, Stroupe AL, Nance TA et al (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24(6):765–773
28. Ireland ML, Ott SM (1994) Special concerns of the female athlete. In: Fu FH, Stone DA (eds) Sports injuries: mechanisms, prevention, and treatment. Williams & Wilkins, Baltimore
29. Iversen MD, Friden C (2009) Pilot study of female high school basketball players' anterior cruciate ligament injury knowledge, attitudes, and practices. Scand J Med Sci Sports 19(4):595–602
30. Janz NK, Becker MH (1984) The health belief model: a decade later. Health Educ Q 11(1):1–47
31. Labella C, Carl R (2010) Preventing knee ligament injuries in young athletes. Pediatr Ann 39(11):714–720
32. Langford JL, Webster KE, Feller JA (2009) A prospective longitudinal study to assess psychological changes following anterior cruciate ligament reconstruction surgery. Br J Sports Med 43(5):377–378

33. Li F, Harmer P, Glasgow R et al (2008) Translation of an effective tai chi intervention into a community-based falls-prevention program. Am J Public Health 98(7):1195–1198
34. Lubowitz JH, Appleby D (2011) Cost-effectiveness analysis of the most common orthopaedic surgery procedures: knee arthroscopy and knee anterior cruciate ligament reconstruction. Arthroscopy 27(10):1317–1322
35. Lund J, Aaro LE (2004) Accident prevention. Presentation of a model placing emphasis on human, structural and cultural factors. Safety Sci 42:271–324
36. McGlashan AJ, Finch CF (2010) The extent to which behavioural and social sciences theories and models are used in sport injury prevention research. Sports Med 40(10):841–858
37. Morrey MA, Stuart MJ, Smith AM et al (1999) A longitudinal examination of athletes' emotional and cognitive responses to anterior cruciate ligament injury. Clin J Sport Med 9(2):63–69
38. Mummery WK, Spence JC, Hudec JC (2000) Understanding physical activity intention in Canadian school children and youth: an application of the theory of planned behavior. Res Q Exerc Sport 71(2):116–124
39. Noyes FR, Barber-Westin SD (2012) Anterior cruciate ligament injury prevention training in female athletes: a systematic review of injury reduction and results of athletic performance tests. Sports Health 4(1):36–46
40. Ochiai S, Hagino T, Tonotsuka H et al (2010) Health-related quality of life in patients with an anterior cruciate ligament injury. Arch Orthop Trauma Surg 130(3):397–399
41. Padua DA, Distefano LJ (2009) Sagittal plane knee biomechanics and vertical ground reaction forces are modified following ACL injury prevention programs: a systematic review. Sports Health 1(2):165–173
42. Padua DA (2010) Executing a collaborative prospective risk-factor study: findings, successes, and challenges. J Athl Train 45(5):519–521
43. Pollard CD, Sigward SM, Ota S et al (2006) The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. Clin J Sport Med 16(3):223–227
44. Reynolds ML, Ransdell LB, Lucas SM et al (2012) An examination of current practices and gender differences in strength and conditioning in a sample of varsity high school athletic programs. J Strength Cond Res 26(1):174–183
45. Rogers EM (1995) Diffusion of innovations, 4th edn. The Free Press, New York
46. Rosenstock IM (1974) Historical origins of the health belief model. Health Educ Monogr 2:328
47. Saunders N, Otago L, Romiti M et al (2010) Coaches' perspectives on implementing an evidence-informed injury prevention programme in junior community netball. Br J Sports Med 44(15):1128–1132
48. Shultz SJ, Schmitz RJ, Nguyen AD et al (2010) ACL research retreat V: an update on ACL injury risk and prevention, March 25–27, 2010, Greensboro, NC. J Athl Train 45(5):499–508
49. Smith HC, Vacek P, Johnson RJ et al (2012) Risk factors for anterior cruciate ligament injury: a review of the literature – part 1: neuromuscular and anatomic risk. Sports Health 4(1):69–78
50. Trifiletti LB, Gielen AC, Sleet DA et al (2005) Behavioral and social sciences theories and models: are they used in unintentional injury prevention research? Health Educ Res 20(3):298–307
51. Twomey D, Finch C, Roediger E et al (2009) Preventing lower limb injuries: is the latest evidence being translated into the football field? J Sci Med Sport 12(4):452–456
52. Udry E, Donald Shelbourne K, Gray T (2003) Psychological readiness for anterior cruciate ligament surgery: describing and comparing the adolescent and adult experiences. J Athl Train 38(2):167–171
53. van Mechelen W, Hlobil H, Kemper HC (1992) Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. Sports Med 14(2):82–99
54. Van Tiggelen D, Wickes S, Stevens V et al (2008) Effective prevention of sports injuries: a model integrating efficacy, efficiency, compliance and risk-taking behaviour. Br J Sports Med 42(8):648–652

22 What We Know and Goals for Future Research

Sandra J. Shultz and Randy J. Schmitz

Contents

S.J. Shultz, Ph.D., A.T.C. (✉)
R.J. Schmitz, Ph.D., A.T.C.
Department of Kinesiology, School of Health and Human Sciences, University of North Carolina at Greensboro, 1408 Walker Ave, Greensboro, NC 27402, USA
e-mail: sjshultz@uncg.edu
e-mail: rjschmit@uncg.edu

Introduction

It is well recognized that multiple factors, whether individually or in combination, contribute to noncontact anterior cruciate ligament (ACL) injury. While our understanding of these contributing factors has increased in recent years, many questions remain that drive continued research in the field. To that end, the ACL Research Retreat was cofounded by Irene Davis, Ph.D., P.T. and Mary Lloyd Ireland, M.D. in 2001 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 [75]. Subsequent retreats have been held in 2003 [76], 2006 [24], 2008 [124], 2010 [127], and 2012. 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. A hallmark of the meeting is the substantial time provided for group discussion after each keynote and thematic free communication session for clinicians and researchers to openly discuss the current state of knowledge in the field and the compelling questions that remain. At the first

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2_22, © Springer-Verlag Berlin Heidelberg 2012

retreat, a consensus document was developed regarding (1) what we know, (2) what remains unknown, and (3) what important directions for future research are needed to address these unknowns [75]. 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 the most recent published updates from ACL Research Retreat V held in Greensboro, North Carolina, on March 25th–27th, 2010, where over 75 clinicians and researchers representing six countries participated in the meeting [127]. The consensus surrounding neuromuscular and biomechanical risk factors, anatomical and structural risk factors, hormonal risk factors, and risk factor screening and prevention is summarized relative to our current understanding and the questions that remain and drive future directions for research. Following these thematic sections, some global observations, themes, and recommendations that emerged from the meeting are included as well.

Neuromuscular and Biomechanical Factors

Neuromuscular and biomechanical (or when considered in combination, neuromechanical) factors are considered to be those factors that are most often obtained during instrumented, biomechanical analyses of human motion. Such factors as joint motion, joint loads, and the magnitude and timing of muscle activation are commonly investigated relative to ACL injury as they are thought to be most modifiable through training. Based on these findings, prevention programs aimed at improving lower extremity neuromechanics have garnered considerable attention in the research community (see section "ACL Injury Prevention").

Current Understanding

A strong mechanistic understanding of joint motions and forces at the knee, coupled with an improved understanding of how other factors both distal (ground reaction forces) and proximal (trunk, hip, torso, arms) to the knee affect motions and forces at the knee, has greatly improved our understanding of how the ACL can come under strain during weight bearing. Additionally, it is accepted that various intrinsic factors such as physical maturation processes and physical exertion (fatigue) likely play a role in how the knee functions during physical activity.

It is well accepted that the ACL can be loaded through a variety of mechanisms that directly impact the knee joint [74, 77, 81, 116, 117, 147, 155, 156]. Recent review papers [116, 155] report that mechanisms such as axial loading, anterior shear, internal rotation, and valgus loads can all increase ACL loading from in vitro and in vivo studies. It is important to note that combined loads and forces from multiple planes can also adversely affect ACL forces [74]. There appeared to be a general consensus that the above-stated mechanisms are to some degree (either in isolation or combination) associated with ACL injury.

When considering factors distal to the knee, the magnitude of ACL strain in weight bearing is related to the magnitude and timing of the vertical ground reaction force [13, 148]. Increased vertical ground reaction forces during the early phase of landing typically occur with a more upright posture (characterized by a more extended knee), which is commonly observed in females during deceleration maneuvers [25, 53, 97, 111]. However, the magnitude of such sex differences may be dependent on the exact deceleration task performed [7]. Regardless, body positions and activities that produce large magnitudes of landing forces are considered detrimental in the ACL injury mechanism.

When considering proximal factors, neuromechanical control of the upper extremity [17], trunk [10, 21, 53, 62], and hip [18, 78, 130] can also influence lower extremity neuromechanics. Specifically, constraint of the upper extremity has been demonstrated to adversely affect valgus loading patterns about the knee during sport-specific maneuvers [17]. A more upright trunk coupled with extended hip and knee postures [10] and greater mechanical demands about distal joints [62] may collectively promote higher-risk dynamic function. Further, larger initial hip flexion and internal rotation during cutting maneuvers is associated with greater peak valgus knee loading [78], while increased hip abductor and adductor co-contraction prior to foot contact may reduce varus and valgus loading about the knee joint [18]. The latter speaks to the importance of neuromuscular control of the trunk and hip in preparation for ground contact in controlling resultant knee loads of increasing demand. Collectively, these data suggest that proximal joint control can have both adverse and beneficial effects as they relate to knee joint function.

Understanding intrinsic processes that change over time both in the long term (such as physical maturation) and in the short term (such as fatigue experienced in bouts of physical activity) is important to our global understanding of neuromuscular and biomechanical factors associated with ACL injury. Physical maturation processes are known to influence a variety of neuromechanical factors [4, 5, 44, 50, 87, 101, 109, 131, 141]. Prepubescent athletes demonstrate a more dynamic knee valgus posture during landings (which is commonly associated with the ACL mechanism in physically mature athletes) [4]. As physical developmental patterns begin to differ between the genders, males undergo a "neuromuscular spurt" that has a protective effect on biomechanical measures during at-risk activities, while developing females do not [101]. The demonstrated changes in the biomechanical function during the maturation process suggest that it may be an ideal time to screen or intervene in individuals thought to be at risk of ACL injury, but this timing has yet to be determined (see section "Questions That Remain and Directions for Future Research").

Short-term changes in neuromechanical function as a result of fatiguing activity are also important. Fatigue has often been associated with altered neuromechanical functioning thought to be "high-risk" for ACL injury [6, 16, 58, 79, 90]. These effects are likely more pronounced in unanticipated conditions, where central processing and subsequent neuromuscular function are compromised [11, 80].

Questions That Remain and Directions for Future Research

There are several recurring themes with resultant-specific research questions that need to be addressed in order to advance the field. Most importantly, the biomechanical/neuromechanical profile of an actual ACL injury event is relatively unknown. Is noncontact ACL injury governed by a single or potentially multiple high-risk neuromechanical profiles? A better understanding of the actual injury event and the activities that pose the greatest loads on the ACL will help focus our future screening and prevention efforts. Also unknown is whether rupture of the ACL is an acute episode (caused by a single event) or a chronic failure (resulting from multiple episodes over time). Although it was generally agreed that more and more is understood about the importance of proximal function relative to knee joint neuromechanics, we still do not know how ACL strain is specifically affected through proximal control (or lack thereof). There is also a need to better simulate the integrated postural strategies observed during at-risk functional tasks so that we can better refine our research models. The impact of movement variability (i.e., whether increased vs. decreased variability is more problematic) continues to be debatable as to its level of applicability to the understanding of noncontact ACL injury risk. Related to this question are the types of measures we should use to evaluate movement variability. Finally, there is an increasing interest in centrally driven factors relative to ACL injury: whether the injury event is the result of an insufficient cognitive response, insufficient mechanical ability, or a combination thereof [99]. Because little research currently exists in this area [80, 139], understanding cognitive factors for ACL injury is a wide-open area of study. To answer these unknowns, Table 22.1 provides specific directions for future research that aims to understand the neuromuscular and biomechanical risk factors for injury.

Anatomical and Structural 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. Included among these factors are ACL geometry and ultrastructure, knee joint geometry, joint laxity, and lower extremity alignment.

Table 22.1 Neuromuscular and biomechanical factors: directions for research

To be able to fully understand contributing factors to ACL strain, improved characterization of the influence of the proximal and distal factors on knee joint biomechanics (ACL loads), and increased focus on the development of improved models (e.g., computational, cadaveric) that noninvasively estimate in vivo ACL forces and strain are required
In order to understand the role of movement variability, neuromechanical variability needs to be examined both within (including between limbs) and between individuals as it relates to ACL injury risk and associated mechanisms
In order to better comprehend the multifactorial nature of the ACL injury, the interaction between anatomic structures, laxity, and neuromechanics in joint-loading profiles needs to be determined, as well as the extent to which they predict ACL injury
Identifying critical thresholds of structural or functional weakness at which compensatory neuromuscular and biomechanical strategies become evident is necessary for future optimization of prevention strategies
To fully understand the role of the central nervous system in ACL injury, research models and analyses must include assessments of central processes (such as automaticity, reaction time), cognitive processes (such as decision making, focus and attention, prior experience), and metacognitive processes (such as monitoring psychomotor processes)
For an improved understanding of dynamic postural strategies that lead to ACL injury, tasks must be developed that are designed to challenge the joint systems in a way that better mimic injury mechanisms. Further, musculoskeletal models describing cause-and-effect relationships have to be studied explicitly within a realistic injury scenario. Care should be taken not to overgeneralize results from one specific task to other tasks with different mechanical demands
To assist in translation of laboratory findings to the field, and field findings to the laboratory, it is necessary to continue validation of commonly performed field assessments (e.g., squatting, landing) to known neuromuscular and biomechanical profiles commonly associated with ACL injury in inherently random sport environments
To contribute to the existing knowledge of transverse and frontal plane knee loadings to ACL injury, more precise transverse and frontal plane measurements need to be developed with improved accuracy and ease of use relative to complex biomechanical measures.
Include comprehensive kinetic, kinematic, and neuromuscular (strength, postural stability, activation, and timing) profiles as integration of these measures to allow for a more complete understanding of movement

Current Understanding

Most of what is known about anatomy and structure are based on comparisons between female and male cohorts (driven by females' greater susceptibility for ACL trauma) and between ACL-injured cases and controls.

ACL Structure and Geometry

When comparing injured to noninjured subjects, ACL-injured individuals have smaller ACLs (area and volume) compared to noninjured controls [20]. When comparing females to males, females are reported to have smaller ACLs relative to length, cross-sectional area, and volume compared to males even after adjusting for body anthropometry [14]. The female ACL has decreased mechanical properties such as strain at failure, stress at failure, and modulus of elasticity even after adjusting for age and body anthropometrics [15]. The ultrastructural analysis of the ACL shows that the percent of the area occupied by collagen fiber (area of collagen fibers/total area of the micrograph) is lower in females when adjusted for age and body anthropometrics [42].

Knee Joint Geometry

Data from magnetic resonance imaging (MRI) studies (which have the potential to image both the lateral and medial tibial plateaus) generally report greater lateral posterior tibial plateau slopes (but not medial tibial slopes) [43, 132, 137], reduced condylar depth of the medial tibial plateau [43], and the presence of an anterior medial ridge on the intercondylar notch [31] in ACL-injured cases versus controls. Females are reported to have greater anterior-to-posterior inferior slope of the lateral and medial tibial plateaus [41, 55] and reduced coronal tibial slopes compared to males [41]. There appears to be no difference between genders in medial tibial plateau depth [41]. The female's femoral notch height is larger, while their femoral notch angle is smaller than males which may influence the femoral notch impingement theory [14]. Femoral notch width and angle are good predictors of ACL size (area and volume) in males but not in females [14].

Joint Laxity

Greater magnitudes of joint laxity have consistently been associated with an increased risk of ACL injury [61, 70, 84, 102, 110, 143, 150]. Clear sex differences in laxity have been observed with females often reported to have greater genu recurvatum [86, 142], anterior knee laxity [8, 107, 110, 120, 143], and general joint laxity [57, 105, 123]. Females are also reported to have 25–30 % greater frontal and transverse plane laxity [54, 73, 114, 122] and reduced torsional stiffness [54, 92, 112] than males. These differences persist even when females and males have similar magnitudes of anterior knee laxity [54, 114, 125]. These greater joint laxities in females have been associated with altered knee joint neuromechanics during weight bearing that are suggestive of higher-risk landing strategies [108, 118, 121, 125, 128].

Lower Extremity Alignment

In adults, females have greater anterior pelvic tilt, hip anteversion, tibiofemoral angle, and quadriceps angle [47, 86]. No sex differences have been observed in measures of tibial torsion [86], navicular drop [47, 86, 142], and rearfoot angle [3, 86]. These lower extremity alignments are different between maturation groups and also develop at different rates in males and females between maturation groups [123], suggesting that the sex differences largely emerge during pubertal development.

Questions That Remain and Directions for Future Research

It is clear that a number of anatomical and structural variables differ between males and females. While many of these anatomical factors have been investigated for their association with ACL injury history and found to be relevant ACL injury risk factors (e.g., ACL geometry, knee joint geometry, knee joint laxity), others have only been examined in a very limited sense (e.g., lower extremity alignment, body composition). For example, there is some evidence that an elevated body mass index (BMI) is predictive of future ACL injury in females [143] and that artificially increasing BMI encourages dangerous biomechanical strategies [62, 63]. While these studies suggest that body composition may be a relevant anatomical risk factor, we still know very little about the influence of body composition on lower extremity neuromechanical strategies or ACL injury risk. A similar case can be made for sex differences in lower extremity alignment.

Of those anatomical factors found to be associated with ACL injury history, it is not yet clear through what mechanism they are influencing risk. In other words, how do intersubject variations in anatomical and structural factors influence knee joint neuromechanics in a way that increases risk? Further, many of these factors have been examined independently, and we have yet to examine the combination of these structural factors in large-scale, multivariate studies to determine which factors are the strongest predictors of ACL injury, or how they combine or interact to pose the greatest strains on the ACL. This is in large part due to the difficulty in measuring these factors reliably using readily available clinical measurement devices. Advances are needed to screen for and investigate these factors in large-scale studies. Other relevant anatomical factors have yet to be accounted for. For example, investigations of knee joint geometry are largely based on measures of the subchondral bone and do not account for the influence of meniscal or cartilage geometry.

Finally, although anatomical and structural factors are often considered non-modifiable once fully mature, we have limited knowledge of how these structural factors change through the maturation process. Also not clear is whether physical activity (or other chronic external loads) can influence the development of these anatomical and structural factors over time, particularly

Table 22.2 Anatomical and structural factors: directions for future research

Although a number of anatomical/structural variables have been associated with a greater risk of ACL injury trauma, there is a need to examine interactions between tibial slope (anterior/posterior, medial/lateral), ACL volume, ACL ultrastructure, femoral notch geometry, condylar geometry, joint laxity, and lower extremity alignment for their potential to increase ACL strain/failure and predict injury risk
In order to determine these interactions and the most important anatomical and structural risk factors for ACL injury, we need to conduct large-scale prospective risk factor studies that account for all relevant lower extremity anatomical and structural factors. Because most anatomical/structural factors are not acutely impacted by the ACL rupture, large, multifactorial case–control study designs should also be considered for examining structural factors
In order to be able to screen a large number of individuals on their anatomical and structural factors in large-scale, multivariate risk factor studies, there is a need to develop more efficient, affordable, reliable, and readily available measurement methods of these anatomical and structural factors
In order to be able to intervene appropriately on these factors in our injury-prevention strategies:
Continued studies are needed to understand how intersubject variations in anatomical and structural factors influence knee joint neuromechanics in a way that increases ACL strain
The underlying factors that cause one to develop "high-risk" anatomical and structural profiles need to be understood. It may be important to consider the influence of additional factors such as body composition changes, muscle properties, stiffness, slack (resting tissue) length, and fatty infiltration
Studies are needed to determine how extrinsic factors (e.g., physical activity) during maturation and across the life span influence these factors. These studies are needed both in adults and maturing youth
In addition to the anatomical factors commonly examined, there is a need to examine the impact of meniscal and cartilage geometry on ACL strain/failure during activity and in ACL-injured cohorts.

during the critical growth periods when structure is changing. If changes do occur as a result of physical activity, when, how, and for how long do the changes occur?

Based on these emerging questions, and the unknowns that remain, recommendations for future investigations of anatomical and structural risk factors are presented in Table 22.2.

Hormonal Factors

A clear difference between males and females that underlie many of the sex-specific characteristics that emerge during puberty is substantial differences in sex steroid hormone concentrations. In particular, the large magnitudes and monthly variations in estrogen and progesterone concentrations that females are exposed to has been an active area of ACL injury risk factor research.

Current Understanding

Evidence in the literature implicates sex hormones as a relevant risk factor for ACL injury. Multiple epidemiological studies suggest that the likelihood of suffering an ACL injury is not evenly distributed across the menstrual cycle, but that the risk may be significantly greater during the preovulatory phase compared to postovulatory phase [2, 9, 85, 135, 149]. During the preovulatory phase, hormone levels are dramatically changing: first falling to their nadirs with the onset of menses and then estrogen rising rapidly and unopposed near the time of ovulation.

The potential for sex hormones to influence knee joint structure and ACL injury risk is based on evidence of sex hormone receptors on the human ACL (such as estrogen, testosterone, and relaxin) [29, 32, 39, 66, 71] and skeletal muscle (such as estrogen, testosterone) [65, 133, 146]. While the influence of hormones on ACL biology has been examined in a variety of animal models [60, 64, 67, 103, 113, 134, 138, 144, 145, 151], these studies offer little consensus of hormone effects on ligament structure and metabolism due to variations in study designs and species examined. Few studies have been conducted in human tissues [157, 158], and research is lacking that directly examines associations between sex hormones, collagen metabolism, and ligament ultrastructure in physically active women who experience normal physiological fluctuations in sex hormone concentrations across the menstrual cycle [104].

At a macroscopic level, multiple studies have reported changes in knee laxity (i.e., anterior knee laxity, genu recurvatum) across the female's menstrual cycle [27, 30, 45, 119, 126]. Subsequently, associations between acute variations in sex hormone concentrations and anterior knee laxity have been observed [119, 121]. However, consistent with substantial intersubject variations in the timing, magnitude, and interactive changes in sex hormones concentrations across the cycle [119, 129], there is considerable variability in the timing and magnitude of cyclic knee laxity changes experienced among women [121, 126]. Although changes in hormone profiles [129] and knee laxity [126] across the menstrual cycle are substantially more consistent within a female from month to month, some variability still exists.

The large intersubject variability in timing, magnitude, and interactive changes in sex hormones concentrations across the cycle needs to be appreciated in our study designs [119], whether examining subsequent knee laxity changes or other metabolic, structural, or biomechanical measures. That is, taking a single measurement time point within a single phase (even with hormone confirmation) is not adequate to accurately characterize the same hormone profile or time point in a particular phase of the menstrual cycle for all females. This inaccuracy may be reduced by taking multiple samples over repeated days to insure one captures the hormone profile of interest [129]. Also important to appreciate is that there is a time dependency effect for sex hormones and other remodeling agents to influence a change in ACL tissue characteristics (i.e., these effects are not immediate) [71, 119]. Moreover, the mechanical and molecular properties of the ACL are likely influenced not only by estrogen but also the interaction of several sex hormones, secondary messengers, remodeling proteins, and mechanical stresses [32, 71, 106, 119, 136, 158]. For example, evidence in animal models suggest that the influence of hormone concentration changes on ACL structure and metabolism may be largely dependent on the mechanical loads that are being placed on the ligament during the time of exposure [22, 23, 64].

Questions That Remain and Directions for Future Research

Because of the known challenges in studying hormone effects on ACL structure and metabolism, knee joint behavior, and ACL injury risk, many questions remain. Although epidemiological studies have consistently pointed to the preovulatory phase as the time when ACL injury is more likely to occur, we understand very little about the underlying mechanism for this increased likelihood. What are the underlying sex-specific hormonal, molecular, and genetic mechanisms of sex hormones on ACL structure, metabolism, and mechanical properties, and how does mechanical stress on the ACL alter these relationships? Another important question is how does the time of injury occurrence line up with acute changes in ACL structure and metabolism or knee laxity changes? Answering this question is complicated by the fact that there is a time lag effect for sex hormones and other remodeling agents to influence a change in ACL tissue characteristics, and this time lag may not be uniform among women. A related question is whether the rate of increase or the time duration of amplitude peaks in hormone fluctuation across the menstrual cycle plays a role in the magnitude or timing of soft tissue changes. To answer these questions, research conducted on physically active females who experience normal physiological changes in hormone concentrations should be a high priority. Comparisons between females who are eumenorrheic, oligomenorrheic, and using oral contraceptives are also needed to determine if ACL injury risk or observed soft tissue changes vary between these groups.

Although cyclic changes in knee laxity have been observed across the menstrual cycle in multiple studies, some important questions remain. Most importantly, we need to understand the clinical implications of these cyclic knee laxity changes on weight-bearing knee

Table 22.3 Hormonal factors: directions for future research

In order to understand the complex relationships between sex hormones, ACL structure and metabolism, and ACL injury risk, we need to:
Define the hormonal, molecular, and genetic mechanisms by which sex hormones effect soft tissue structures
Understand the hormonal, molecular, and genetic mechanisms that explain the gender-specific differences in ACL structure, metabolism, and mechanical properties that have been observed
Examine interaction between hormones, mechanical loading, and ACL mechanical properties
Answer these questions using study designs relevant to the healthy, physically active female
When examining hormone influences on knee joint function and ACL injury risk in physically active females, we should:
Focus more on individual results rather than mean values, as there is much variability in individual menstrual cycle characteristics (this may help explain why some females are more at risk than others)
Develop improved methods to measure individual hormone profiles to better match the complexity of intersubject differences in timing, magnitude, and interactive changes in sex hormones concentrations across the cycle. At minimum these should include (1) verifying phases of the cycle with actual hormones measures (considering all relevant hormones to include estrogen, progesterone, and possibly others) to confirm that the desired time in the cycle or a particular phase is truly captured in future study designs and (2) obtaining hormone samples over multiple days rather than rely on measurements taken at a single time point
Examine females using oral contraceptive and those with irregular menstrual cycles (amenorrheic, oligomenorrheic). The type of contraceptive should be documented and both the endogenous and exogenous levels of sex hormones examined
When making female to male comparisons on any risk factors where acute fluctuations in hormones have the potential to confound the anatomical, neuromuscular, and biomechanical outcomes of interest (e.g., knee joint laxity, landing neuromechanics, muscle strength), variables should be collected during the early follicular phase when hormone levels are at their nadirs (preferably 3–7 days post menses)
To establish any genetic components to ACL injury, we need to encourage examination of ACL injury in genome-wide associate studies

joint function and ACL injury risk. While there is some evidence that small cyclic variations in anterior knee laxity may be sufficient to alter knee joint neuromechanics [93, 94], more work is needed to characterize these changes and determine if they are sufficient to negatively influence ACL strain and failure. If we find that these cyclic knee laxity changes are of sufficient magnitude to influence injury risk, we then need to better understand why some women experience large cyclic changes in knee laxity while others do not.

Finally, little is known about the role of sex hormones on skeletal muscle structure and function in controlling dynamic motion. What, if any, changes occur in neuromuscular and biomechanical risk factors across the menstrual cycle? Although previous studies have suggested that cyclical changes in neuromuscular and biomechanical control may be negligible [1, 19, 26], these results may be incomplete due the lack of sophistication of study designs in light of the individual variations in hormone profiles previously described. It will be important in the future to improve our study designs to better capture the complexity of these sex hormone profiles.

Based on these important questions, and the many unknowns that remain, recommendations for future investigations of hormonal risk factors are presented in Table 22.3.

Risk Factor Screening

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) as well as extrinsic (footwear, sporting environment, training) factors. Because ACL injury remains a relatively rare event, there is a clear need to develop accurate and easily obtainable screening measures to identify those at risk of ACL injury so that we can identify and target these individuals specifically in our ACL injury-prevention strategies.

Table 22.4 Risk factor screening: directions for research

To strengthen and expand monitoring of long-term trends in ACL incidence, ongoing injury-surveillance systems should be combined with the establishment of population-based registries of ACL injuries
In order to facilitate cross study comparisons, standardized operational definitions for ACL injury incidence and injury prevalence should be developed and adopted
To better understand ACL injury with respect to age, maturation, sex, sport, and experience level, epidemiologic studies need to be performed in a variety of populations
We need to determine if prospective risk factors for ACL reinjury are similar to those of the initial ACL injury
To further our knowledge of other epidemiologic factors, we need to understand the consequences of ACL injury on future health and other outcomes (such as lost school time), as well as define direct and indirect costs of sport-related ACL injuries
To allow the most accurate identification of those at risk, we need to continue to develop and validate other field-assessment and screening protocols that identify individuals at risk for ACL injury

Current Understanding

Cohort studies of ACL injury risk suggest that prior history of ACL injury is a risk factor for a subsequent ACL injury on the ipsilateral or contralateral side [115, 140, 152]. Family history of ACL injury also appears to increase injury risk [34, 40, 98]. Such risk factors are quite easily measured and obtained and should be a part a comprehensive risk factor screening for ACL injury.

Non-laboratory measures of risk factors that can be obtained in the "field" may be beneficial in screening for those individuals with an increased risk of ACL injury [91]. Such measures are characterized by relatively simple clinical instrumentation (such as video camera, tape measure, goniometer) and are not time consuming in nature. Such developments could allow for accurate and time-effective screening of greater numbers of athletic participants at risk for ACL injury.

Questions That Remain and Directions for Future Research

There is an expressed need to further define the epidemiology of ACL injury, including the identification of individual risk factors and potential interactions among these risk factors (e.g., predictive risk profiles). However, given the relatively low incidence of noncontact ACL injury compared to other musculoskeletal injuries (such as ankle sprains), there are significant challenges in answering these questions. Although difficult to conduct, prospective, multifactorial risk factor studies continue to be important if we are to identify the most important combination of risk factors for ACL injury. Although family history [34, 40, 98] and one's own personal history of ACL injury [115, 140, 152] appear to increase the risk of future ACL injury, the underlying factors for this elevated risk are unknown. 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. Also unknown is the impact of physical activity (or inactivity), including the availability of physical education in schools, on ACL injury risk or associated risk factors: information that may be critical to our future risk factor screening and prevention efforts. To better understand the multifactorial nature of ACL injury risk, and how we can better identify those at greatest risk, Table 22.4 lists recommended directions for future research in the area of risk factor screening.

ACL Injury Prevention

ACL injuries can affect long-term health and well-being via the development of posttraumatic knee osteoarthritis [12, 59, 68, 69]. It is estimated that approximately 50% of individuals will develop osteoarthritis with associated pain and functional impairment within 10–20 years after the diagnosis of an ACL injury or meniscus tear [69]. This impact on quality of life and long-term health outcomes is a clear driving force to prevent the primary knee injury from occurring [68].

Current Understandings

Programs designed to prevent noncontact ACL injury are common in the athletic setting. These prevention programs often include (but are not limited to) exercise components of strength, plyometrics, balance training, motor reeducation and feedback, and flexibility. When these components have been incorporated into prevention programs under study, various biomechanical and neuromuscular variables thought to contribute to ACL injury are positively affected [46, 48, 56, 82, 83, 89, 96]. Such demonstrated beneficial effects include decreased impact forces [48, 83], enhanced muscle recruitment [56], improved balance [82], reduced knee valgus [82], lesser hip internal rotation [96], and greater hip abduction [96]. But while various studies of ACL prevention programs have demonstrated a reduced incidence of ACL injury (although not always statistically significant) [35, 49, 51, 72, 85, 88, 153], the sex disparity in injury incidence has not abated [52]. Additionally, the physiological/biomechanical processes affected by common physical training protocols are demonstrated to be transient in nature [37, 38, 95]. This suggests we have yet to fully optimize our ACL prevention efforts.

Questions That Remain and Directions for Future Research

Currently, the base mechanism(s) of effective ACL prevention programs is still unknown as most prevention programs include multiple training modes (strengthening, balance, reactive activity, education and feedback, etc.) as noted above. Because the programs that have been studied introduced these components simultaneously and to varying degrees, many questions remain. Specifically, what are the specific training mode(s) by which the protective effect is transferred? What is the magnitude of training stimulus (frequency and duration of training) necessary for the intervention to be effective (and optimized)? What is the ability of individuals to retain the beneficial effects of preventative programs and for how long? Finally, does participation in an ACL prevention program affect overall participation in physical activity (through continuous athletic involvement)?

The age at which prevention programs should begin is also a subject of debate. Given what is known about the physical maturation process affecting numerous biomechanical and neuromuscular factors, intervening at a relatively young maturational age would seem to be of benefit [4, 5, 44, 50, 87, 101, 109, 141]. However, current programs do not appear to be as successful in pediatric age groups as they are in adults [28, 36]. This raises the question whether prevention programs need to be tailored to specific sports, specific ages, or an individual athlete's needs. While evidence suggests that injury-prevention programs may be more effective for soccer than basketball [100], most prevention programs have been designed for and tested on soccer and team handball athletes.

From a public health perspective, it is unknown what individual, organizational, and socioeconomic factors may affect successful implementation of ACL injury-prevention programs in a variety of settings. Related to this concept, there is incomplete data on the barriers and facilitators associated with compliance of injury-prevention programs. To address these important questions, Table 22.5 lists the recommendations for future research in ACL injury prevention.

Some Global Observations

In addition to updating our knowledge in the five areas previously discussed, some global observations, themes, and recommendations emerged from the meeting that do not fit in a single category but also deserve mention. In response to issues raised at a previous retreat [124], there appears to be a movement away from purely descriptive sex comparison studies which have tended to dominate the literature toward a greater focus on understanding the underlying mechanisms associated with the observed sex differences, and more directly, ACL injury risk, and prevention. However, there is still a clear need to

Table 22.5 ACL injury prevention: directions for research

To understand the mechanisms underlying an injury-prevention program's success or failure, we need to:
Uncover the essential elements (e.g., strengthening, plyometrics) and training stimuli (frequency, intensity, duration) of successful programs that produce the desired protective effect
Determine program specificity with regard to sport, maturation, and level of experience
Clarify how training programs can address issues related to fatigue
Determine the optimal timing of the intervention relative to the sport season
Determine how long the positive effects of the training programs last after the intervention is completed (i.e., when is a booster needed?)
Determine perceived barriers, attitudes, and motivations related to compliance with injury-prevention programs
Determine the personal characteristics of those who do and do not favorably respond to ACL injury-prevention programs
Ascertain the cost-effectiveness of ACL injury-prevention strategies
Evaluate if injury-prevention programs can positively or negatively affect athletic performance
To facilitate translational research to implement ACL injury-prevention programs into community settings to maximize public health effects, we need to:
Evaluate the benefits of population (everyone receives the intervention) versus targeted (only high-risk individuals receive the intervention) approaches to determine best practices for dissemination of ACL injury-prevention strategies
Apply and translate the Translating Research into Injury Prevention Practice (TRIPP) model of injury prevention [33] for the ACL
Develop organizational partnerships (sports governing bodies, coaches, and school-based organizations; professional organizations such as the National Athletic Trainers' Association, American Physical Therapy Association, and American Orthopaedic Society for Sports Medicine) to better understand barriers to implementation and to improve compliance and program effectiveness
To expand on current preventative efforts we need to develop and evaluate new ACL injury-prevention interventions, including educational programs, sport-specific conditioning and training, and novel modification of anatomical and hormonal factors

take a more integrated approach in our research to better understand the multifactorial nature of the ACL injury enigma. This involves examining all relevant anatomical (such as posture, structure, body composition) and structural (such as tibial slope, condylar geometry) factors, as well as the associated neuromechanical outcomes (e.g., integrated findings from kinetic, kinematic, and neuromuscular measures) used in the examination of these risk factors. The former is particularly challenging, given the relatively low incidence of ACL injury in comparison to other injuries such as ankle sprains. Because of this, traditional risk factor designs such as prospective cohort studies (although needed) may not advance our scientific understanding of the ACL injury mechanism at a rate rapid enough to begin to better prevent these injuries.

To offset these challenges, there is a critical need to develop open source databases (including video registries, open source software models, etc.) in order to pool our resources. Development of complimentary new measurement paradigms are also encouraged, both to allow more rapid scientific advancement of the understanding of the ACL injury mechanism and related risk factors, and to gain a more integrated understanding of this complex, multifactorial problem. These include continued emphases on computer and cadaveric modeling to allow multifactorial manipulation in a way that would not be possible in vivo, and the use of state-of-the-art robotic simulations to better understand complex relationships between muscle force production, joint and ligament morphology, and resultant ACL strain. More functional testing conditions performed in vivo are needed to help resolve cognitive/supraspinal/spinal contributions to knee joint and ACL loading within the truly random movement environment synonymous with game play. The role of behavior and cognition have received relatively little attention as compared to more traditional risk factor categories, yet previous work [80, 139] and the keynote presentation by Christopher Powers [99] provide compelling evidence of the need to explore these areas of research with greater intensity. Addressing these and other unknowns is critical to our continued development and refinement of injury risk screening and prevention programs. Although a primary focus of some prevention programs to date has been to eliminate certain movement patterns (e.g., reducing knee valgus), the evidence supporting any one mechanism alone is quite weak. Thus, while these programs have shown some success and should continue, the ideal prevention program for ACL injury may not be realized until we have a better grasp on this complex, multifactorial problem.

Another general consideration raised at this meeting was the need to increase our focus on the youth athlete and to take a more public health approach in our injury risk screening and prevention strategies in this population. Although it is postulated that the best time to identify and counter risk is during the adolescent years, we still know very little about when relevant risk factors emerge, when intervention should be initiated, or how we can improve inclusion, compliance, and effectiveness of ACL injury-prevention programs in this target population. This is particularly relevant, as there is evidence that children and adolescents perform athletic tasks differently than adults [50, 101, 141, 154] and recent research suggests that the response to injury-prevention programs may differ across different age groups [28, 36]. Additionally, there is great concern regarding the continuing trends of inactivity and obesity (e.g., loss of physical education classes in US schools) and how this may impact acquisition of general motor programs and skill development and their ultimate impact on prospective ACL injury risk. Another important public health concern is the consequences of ACL injury so early in life on short-term (e.g., lost school time) and future quality of life (e.g., osteoarthritis, inactivity). To that end, there is a call for a greater understanding of the prospective risk factors for ACL injury in the maturing youth population; a greater understanding of the cognitive, behavioral, and socioeconomical factors that influence successful implementation of ACL injury awareness and prevention programs in youth sport participants; and a movement toward more translational approaches to implementation of ACL injury-prevention programs into community settings to maximize public health impact.

Summary

Clearly, many questions remain that drive our future research toward a better understanding of the epidemiology and etiology of ACL injury and the development of effective risk factor screening and injury-prevention efforts. It is our hope that the insights from this meeting will continue to strengthen the foundation upon which quality research and clinical interventions in ACL injury risk and prevention can be advanced.

Acknowledgements The content of this chapter was adapted from Shultz et al. [127] and reproduced with permission from the *Journal of Athletic Training*.

References

1. Abt JP, Sell TC, Laudner KG et al (2007) Neuromuscular and biomechanical characteristics do not vary across the menstrual cycle. Knee Surg Sports Traumatol Arthrosc 15(7):901–907
2. Arendt EA, Bershadsky B, Agel J (2002) Periodicity of noncontact anterior cruciate ligament injuries during the menstrual cycle. J Gend Specif Med 5(2):19–26
3. Astrom M, Arvidson T (1995) Alignment and joint motion in the normal foot. J Orthop Sports Phys Ther 22(5):216–222
4. Barber-Westin SD, Galloway M, Noyes FR et al (2005) Assessment of lower limb neuromuscular control in prepubescent athletes. Am J Sports Med 33(12): 1853–1860
5. Barber-Westin SD, Noyes FR, Galloway M (2006) Jump-land characteristics and muscle strength development in young athletes: a gender comparison of 1140 athletes 9 to 17 years of age. Am J Sports Med 34(3):375–384
6. Benjaminse A, Habu A, Sell TC et al (2008) Fatigue alters lower extremity kinematics during a single-leg stop-jump task. Knee Surg Sports Traumatol Arthrosc 16(4):400–407
7. Benjaminse A, Lemmink KA, Diercks RL et al (2010) An investigation of motor learning during side-step cutting: design of a randomised controlled trial. BMC Musculoskelet Disord 11:235

8. Beynnon BD, Bernstein IM, Belisle A et al (2005) The effect of estradiol and progesterone on knee and ankle joint laxity. Am J Sports Med 33(9):1298–1304
9. Beynnon BD, Johnson RJ, Braun S et al (2006) The relationship between menstrual cycle phase and anterior cruciate ligament injury: a case–control study of recreational alpine skiers. Am J Sports Med 34(5):757–764
10. Blackburn JT, Padua DA (2008) Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. Clin Biomech (Bristol, Avon) 23(3):313–319
11. Borotikar BS, Newcomer R, Koppes R et al (2008) Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. Clin Biomech (Bristol, Avon) 23(1):81–92
12. Brown TD, Johnston RC, Saltzman CL et al (2006) Posttraumatic osteoarthritis: a first estimate of incidence, prevalence, and burden of disease. J Orthop Trauma 20(10):739–744
13. Cerulli G, Benoit DL, Lamontagne M et al (2003) In vivo anterior cruciate ligament strain behaviour during a rapid deceleration movement: case report. Knee Surg Sports Traumatol Arthrosc 11(5):307–311
14. Chandrashekar N, Slauterbeck J, Hashemi J (2005) Sex-based differences in the anthropometric characteristics of the anterior cruciate ligament and its relation to intercondylar notch geometry: a cadaveric study. Am J Sports Med 33(10):1492–1498
15. Chandrashekar N, Mansouri H, Slauterbeck J et al (2006) Sex-based differences in the tensile properties of the human anterior cruciate ligament. J Biomech 39(16):2943–2950
16. Chappell JD, Herman DC, Knight BS et al (2005) Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. Am J Sports Med 33(7): 1022–1029
17. Chaudhari AM, Hearn BK, Andriacchi TP (2005) Sport-dependent variations in arm position during single-limb landing influence knee loading: implications for anterior cruciate ligament injury. Am J Sports Med 33(6):824–830
18. Chaudhari AM, Andriacchi TP (2006) The mechanical consequences of dynamic frontal plane limb alignment for non-contact ACL injury. J Biomech 39(2):330–338
19. Chaudhari AM, Lindenfeld TN, Andriacchi TP et al (2007) Knee and hip loading patterns at different phases in the menstrual cycle: implications for the gender difference in anterior cruciate ligament injury rates. Am J Sports Med 35(5):793–800
20. Chaudhari AM, Zelman EA, Flanigan DC et al (2009) Anterior cruciate ligament-injured subjects have smaller anterior cruciate ligaments than matched controls: a magnetic resonance imaging study. Am J Sports Med 37(7):1282–1287
21. Chaudhari AM, Jamison ST (2010) Influence of trunk neuromuscular control on run-to-cut maneuver: a risk factor for ACL rupture. J Athl Train 45(5):522
22. Comerford EJ, Tarlton JF, Innes JF et al (2005) Metabolism and composition of the canine anterior cruciate ligament relate to differences in knee joint mechanics and predisposition to ligament rupture. J Orthop Res 23(1):61–66
23. Comerford EJ, Tarlton JF, Avery NC et al (2006) Distal femoral intercondylar notch dimensions and their relationship to composition and metabolism of the canine anterior cruciate ligament. Osteoarthritis Cartilage 14(3):273–278
24. Davis I, Ireland ML, Hanaki S (2007) ACL injuries – the gender bias. J Orthop Sports Phys Ther 37(2):A2–A7
25. Decker MJ, Torry MR, Wyland DJ et al (2003) Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. Clin Biomech (Bristol, Avon) 18(7):662–669
26. Dedrick GS, Sizer PS, Merkle JN et al (2008) Effect of sex hormones on neuromuscular control patterns during landing. J Electromyogr Kinesiol 18(1):68–78
27. Deie M, Sakamaki Y, Sumen Y et al (2002) Anterior knee laxity in young women varies with their menstrual cycle. Int Orthop 26(3):154–156
28. DiStefano LJ, Padua DA, DiStefano MJ et al (2009) Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. Am J Sports Med 37(3):495–505
29. Dragoo JL, Lee RS, Benhaim P et al (2003) Relaxin receptors in the human female anterior cruciate ligament. Am J Sports Med 31(4):577–584
30. Eiling E, Bryant AL, Petersen W et al (2007) Effects of menstrual-cycle hormone fluctuations on musculotendinous stiffness and knee joint laxity. Knee Surg Sports Traumatol Arthrosc 15(2):126–132
31. Everhart JS, Flanigan DC, Simon RA et al (2010) Association of noncontact anterior cruciate ligament injury with presence and thickness of a bony ridge on the anteromedial aspect of the femoral intercondylar notch. Am J Sports Med 38(8):1667–1673
32. Faryniarz DA, Bhargava M, Lajam C et al (2006) Quantitation of estrogen receptors and relaxin binding in human anterior cruciate ligament fibroblasts. In Vitro Cell Dev Biol Anim 42(7):176–181
33. Finch C (2006) A new framework for research leading to sports injury prevention. J Sci Med Sport 9(1–2):3–9; discussion 10
34. Flynn RK, Pedersen CL, Birmingham TB et al (2005) The familial predisposition toward tearing the anterior cruciate ligament: a case control study. Am J Sports Med 33(1):23–28
35. Gilchrist J, Mandelbaum BR, Melancon H et al (2008) A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. Am J Sports Med 36(8): 1476–1483
36. Grandstrand SL, Pfeiffer RP, Sabick MB et al (2006) The effects of a commercially available warm-up program on landing mechanics in female youth soccer players. J Strength Cond Res 20(2):331–335

37. Graves JE, Martin AD, Miltenberger LA et al (1988) Physiological responses to walking with hand weights, wrist weights, and ankle weights. Med Sci Sports Exerc 20(3):265–271
38. Hakkinen K, Alen M, Kraemer WJ et al (2003) Neuromuscular adaptations during concurrent strength and endurance training versus strength training. Eur J Appl Physiol 89(1):42–52
39. Hamlet WP, Liu SH, Panossian V et al (1997) Primary immunolocalization of androgen target cells in the human anterior cruciate ligament. J Orthop Res 15(5):657–663
40. Harner CD, Paulos LE, Greenwald AE et al (1994) Detailed analysis of patients with bilateral anterior cruciate ligament injuries. Am J Sports Med 22(1):37–43
41. Hashemi J, Chandrashekar N, Gill B et al (2008) The geometry of the tibial plateau and its influence on the biomechanics of the tibiofemoral joint. J Bone Joint Surg Am 90(12):2724–2734
42. Hashemi J, Chandrashekar N, Mansouri H et al (2008) The human anterior cruciate ligament: sex differences in ultrastructure and correlation with biomechanical properties. J Orthop Res 26(7):945–950
43. Hashemi J, Chandrashekar N, Mansouri H et al (2010) Shallow medial tibial plateau and steep medial and lateral tibial slopes: new risk factors for anterior cruciate ligament injuries. Am J Sports Med 38(1):54–62
44. Hass CJ, Schick EA, Tillman MD et al (2005) Knee biomechanics during landings: comparison of pre- and postpubescent females. Med Sci Sports Exerc 37(1):100–107
45. Heitz NA, Eisenman PA, Beck CL et al (1999) Hormonal changes throughout the menstrual cycle and increased anterior cruciate ligament laxity in females. J Athl Train 34(2):144–149
46. Herman DC, Onate JA, Weinhold PS et al (2009) The effects of feedback with and without strength training on lower extremity biomechanics. Am J Sports Med 37(7):1301–1308
47. Hertel JN, Dorfman JH, Brahan RA (2004) Lower extremity malalignment and anterior cruciate ligament injury history. J Sports Sci Med 3:220–225
48. Hewett TE, Stroupe AL, Nance TA et al (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24(6):765–773
49. Hewett TE, Lindenfeld TN, Riccobene JV et al (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27(6):699–706
50. Hewett TE, Myer GD, Ford KR (2004) Decrease in neuromuscular control about the knee with maturation in female athletes. J Bone Joint Surg Am 86-A(8):1601–1608
51. Hewett TE, Ford KR, Myer GD (2006) Anterior cruciate ligament injuries in female athletes: part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. Am J Sports Med 34(3): 490–498
52. Hootman JM, Dick R, Agel J (2007) Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. J Athl Train 42(2):311–319
53. Houck JR, Duncan A, De Haven KE (2006) Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. Gait Posture 24(3):314–322
54. Hsu WH, Fisk JA, Yamamoto Y et al (2006) Differences in torsional joint stiffness of the knee between genders: a human cadaveric study. Am J Sports Med 34(5):765–770
55. Hudek R, Fuchs B, Regenfelder F et al (2011) Is noncontact ACL injury associated with the posterior tibial and meniscal slope? Clin Orthop Relat Res 469(8):2377–2384
56. Hurd WJ, Chmielewski TL, Snyder-Mackler L (2006) Perturbation-enhanced neuromuscular training alters muscle activity in female athletes. Knee Surg Sports Traumatol Arthrosc 14(1):60–69
57. Jansson A, Saartok T, Werner S et al (2004) General joint laxity in 1845 Swedish school children of different ages: age- and gender-specific distributions. Acta Paediatr 93(9):1202–1206
58. Kernozek TW, Torry MR, Iwasaki M (2008) Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. Am J Sports Med 36(3):554–565
59. Kessler MA, Behrend H, Henz S et al (2008) Function, osteoarthritis and activity after ACL-rupture: 11 years follow-up results of conservative versus reconstructive treatment. Knee Surg Sports Traumatol Arthrosc 16(5):442–448
60. Komatsuda T, Sugita T, Sano H et al (2006) Does estrogen alter the mechanical properties of the anterior cruciate ligament? An experimental study in rabbits. Acta Orthop 77(6):973–980
61. Kramer LC, Denegar CR, Buckley WE et al (2007) Factors associated with anterior cruciate ligament injury: history in female athletes. J Sports Med Phys Fitness 47(4):446–454
62. Kulas A, Zalewski P, Hortobagyi T et al (2008) Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landings. J Biomech 41(1):180–185
63. Kulas AS, Hortobagyi T, Devita P (2010) The interaction of trunk-load and trunk-position adaptations on knee anterior shear and hamstrings muscle forces during landing. J Athl Train 45(1): 5–15
64. Lee CY, Liu X, Smith CL et al (2004) The combined regulation of estrogen and cyclic tension on fibroblast biosynthesis derived from anterior cruciate ligament. Matrix Biol 23(5):323–329
65. Lemoine S, Granier P, Tiffoche C et al (2003) Estrogen receptor alpha mrna in human skeletal muscles. Med Sci Sports Exerc 35(3):439–443
66. Liu SH, al Shaikh R, Panossian V et al (1996) Primary immunolocalization of estrogen and progesterone

target cells in the human anterior cruciate ligament. J Orthop Res 14(4):526–533
67. Liu SH, Al-Shaikh RA, Panossian V et al (1997) Estrogen affects the cellular metabolism of the anterior cruciate ligament. A potential explanation for female athletic injury. Am J Sports Med 25(5):704–709
68. Lohmander LS, Ostenberg A, Englund M et al (2004) High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum 50(10):3145–3152
69. Lohmander LS, Englund PM, Dahl LL et al (2007) The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. Am J Sports Med 35(10):1756–1769
70. Loudon JK, Jenkins W, Loudon KL (1996) The relationship between static posture and ACL injury in female athletes. J Orthop Sports Phys Ther 24(2):91–97
71. Lovering RM, Romani WA (2005) Effect of testosterone on the female anterior cruciate ligament. Am J Physiol Regul Integr Comp Physiol 289(1):R15–R22
72. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010
73. Markolf KL, Graff-Radford A, Amstutz HC (1978) In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. J Bone Joint Surg Am 60(5):664–674
74. Markolf KL, Burchfield DM, Shapiro MM et al (1995) Combined knee loading states that generate high anterior cruciate ligament forces. J Orthop Res 13(6):930–935
75. McClay Davis I, Ireland ML (2001) ACL research retreat: the gender bias. April 6–7, 2001. Meeting report and abstracts. Clin Biomech (Bristol, Avon) 16(10):937–959
76. McClay Davis I, Ireland ML (2003) ACL injuries – the gender bias. J Orthop Sports Phys Ther 33(8):A2–A8
77. McLean SG, Huang X, Su A et al (2004) Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. Clin Biomech (Bristol, Avon) 19(8):828–838
78. McLean SG, Huang X, van den Bogert AJ (2005) Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. Clin Biomech (Bristol, Avon) 20(8):863–870
79. McLean SG, Fellin RE, Suedekum N et al (2007) Impact of fatigue on gender-based high-risk landing strategies. Med Sci Sports Exerc 39(3):502–514
80. McLean SG, Samorezov JE (2009) Fatigue-induced ACL injury risk stems from a degradation in central control. Med Sci Sports Exerc 41(8):1661–1672
81. Meyer EG, Haut RC (2010) Biomechanical response of the knee to injury level forces in sports loading scenarios. J Athl Train 45(4):534
82. Myer GD, Ford KR, Brent JL et al (2006) he effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. J Strength Cond Res 20(2):345–353
83. Myer GD, Ford KR, McLean SG et al (2006) The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. Am J Sports Med 34(3):445–455
84. Myer GD, Ford KR, Paterno MV et al (2008) The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. Am J Sports Med 36(6):1073–1080
85. Myklebust G, Engebretsen L, Braekken IH et al (2003) Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. Clin J Sport Med 13(2):71–78
86. Nguyen AD, Shultz SJ (2007) Sex differences in clinical measures of lower extremity alignment. J Orthop Sports Phys Ther 37(7):389–398
87. 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
88. Olsen OE, Myklebust G, Engebretsen L et al (2005) Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. BMJ 330(7489):449
89. Onate JA, Guskiewicz KM, Marshall SW et al (2005) Instruction of jump-landing technique using videotape feedback: altering lower extremity motion patterns. Am J Sports Med 33(6):831–842
90. Orishimo KF, Kremenic IJ (2006) Effect of fatigue on single-leg hop landing biomechanics. J Appl Biomech 22(4):245–254
91. Padua DA, Marshall SW, Beutler AL et al (2010) The landing error scoring system (less) prospectively identifies ACL injury. J Athl Train 45(5):539
92. Park HS, Wilson NA, Zhang LQ (2008) Gender differences in passive knee biomechanical properties in tibial rotation. J Orthop Res 26(7):937–944
93. Park SK, Stefanyshyn DJ, Ramage B et al (2009) Alterations in knee joint laxity during the menstrual cycle in healthy women leads to increases in joint loads during selected athletic movements. Am J Sports Med 37(6):1169–1177
94. Park SK, Stefanyshyn DJ, Ramage B et al (2009) Relationship between knee joint laxity and knee joint mechanics during the menstrual cycle. Br J Sports Med 43(3):174–179
95. Petibois C, Deleris G (2003) Effects of short- and long-term detraining on the metabolic response to endurance exercise. Int J Sports Med 24(5): 320–325
96. Pollard CD, Sigward SM, Ota S et al (2006) The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. Clin J Sport Med 16(3): 223–227

97. Pollard CD, Sigward SM, Powers CM (2007) Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. Clin J Sport Med 17(1):38–42
98. Posthumus M, September AV, O'Cuinneagain D et al (2009) The col5a1 gene is associated with increased risk of anterior cruciate ligament ruptures in female participants. Am J Sports Med 37(11):2234–2240
99. Powers CM, Fisher B (2010) Mechanisms underlying ACL injury-prevention training: the brain-behavior relationship. J Athl Train 45(5):513–515
100. Prodromos CC, Han Y, Rogowski J et al (2007) A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. Arthroscopy 23(12): 1325e1–1325e6
101. Quatman CE, Ford KR, Myer GD et al (2006) Maturation leads to gender differences in landing force and vertical jump performance: a longitudinal study. Am J Sports Med 34(5):806–813
102. Ramesh R, Von Arx O, Azzopardi T et al (2005) The risk of anterior cruciate ligament rupture with generalised joint laxity. J Bone Joint Surg Br 87(6):800–803
103. Rau MD, Renouf D, Benfield D et al (2005) Examination of the failure properties of the anterior cruciate ligament during the estrous cycle. Knee 12(1):37–40
104. Renstrom P, Ljungqvist A, Arendt E et al (2008) Non-contact ACL injuries in female athletes: an international Olympic committee current concepts statement. Br J Sports Med 42(6):394–412
105. Rikken-Bultman DG, Wellink L, van Dongen PW (1997) Hypermobility in two Dutch school populations. Eur J Obstet Gynecol Reprod Biol 73(2):189–192
106. Romani W, Patrie J, Curl LA et al (2003) The correlations between estradiol, estrone, estriol, progesterone, and sex hormone-binding globulin and anterior cruciate ligament stiffness in healthy, active females. J Womens Health (Larchmt) 12(3):287–298
107. Rosene JM, Fogarty TD (1999) Anterior tibial translation in collegiate athletes with normal anterior cruciate ligament integrity. J Athl Train 34(2):93–98
108. Rozzi SL, Lephart SM, Gear WS et al (1999) Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. Am J Sports Med 27(3):312–319
109. Russell PJ, Croce RV, Swartz EE et al (2007) Knee-muscle activation during landings: developmental and gender comparisons. Med Sci Sports Exerc 39(1):159–170
110. Scerpella TA, Stayer TJ, Makhuli BZ (2005) Ligamentous laxity and non-contact anterior cruciate ligament tears: a gender-based comparison. Orthopedics 28(7):656–660
111. Schmitz RJ, Kulas AS, Perrin DH et al (2007) Sex differences in lower extremity biomechanics during single leg landings. Clin Biomech (Bristol, Avon) 22(6):681–688
112. Schmitz RJ, Ficklin TK, Shimokochi Y et al (2008) Varus/valgus and internal/external torsional knee joint stiffness differs between sexes. Am J Sports Med 36(7):1380–1388
113. Seneviratne A, Attia E, Williams RJ et al (2004) The effect of estrogen on ovine anterior cruciate ligament fibroblasts: cell proliferation and collagen synthesis. Am J Sports Med 32(7):1613–1618
114. Sharma L, Lou C, Felson DT et al (1999) Laxity in healthy and osteoarthritic knees. Arthritis Rheum 42(5):861–870
115. Shelbourne KD, Gray T, Haro M (2009) Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med 37(2):246–251
116. Shimokochi Y, Shultz SJ (2008) Mechanisms of noncontact anterior cruciate ligament injury. J Athl Train 43(4):396–408
117. Shin CS, Chaudhari AM, Andriacchi TP (2007) The influence of deceleration forces on ACL strain during single-leg landing: a simulation study. J Biomech 40(5):1145–1152
118. Shultz SJ, Carcia CR, Perrin DH (2004) Knee joint laxity affects muscle activation patterns in the healthy knee. J Electromyogr Kinesiol 14(4): 475–483
119. Shultz SJ, Kirk SE, Johnson ML et al (2004) Relationship between sex hormones and anterior knee laxity across the menstrual cycle. Med Sci Sports Exerc 36(7):1165–1174
120. Shultz SJ, Sander TC, Kirk SE et al (2005) Sex differences in knee joint laxity change across the female menstrual cycle. J Sports Med Phys Fitness 45:594–603
121. Shultz SJ, Gansneder BM, Sander TC et al (2006) Absolute serum hormone levels predict the magnitude of change in anterior knee laxity across the menstrual cycle. J Orthop Res 24(2):124–131
122. Shultz SJ, Shimokochi Y, Nguyen AD et al (2007) Measurement of varus-valgus and internal-external rotational knee laxities in vivo-part ii: relationship with anterior-posterior and general joint laxity in males and females. J Orthop Res
123. Shultz SJ, Nguyen AD, Schmitz RJ (2008) Differences in lower extremity anatomical and postural characteristics in males and females between maturation groups. J Orthop Sports Phys Ther 38(3):137–149
124. Shultz SJ, Schmitz RJ, Nguyen AD (2008) Research retreat iv: ACL injuries – the gender bias: April 3–5, 2008 Greensboro, NC. J Athl Train 43(5):530–531
125. Shultz SJ, Schmitz RJ (2009) Effects of transverse and frontal plane knee laxity on hip and knee neuromechanics during drop landings. Am J Sports Med 37(9):1821–1830
126. Shultz SJ, Levine BJ, Nguyen AD et al (2010) A comparison of cyclic variations in anterior knee laxity, genu recurvatum, and general joint laxity across the menstrual cycle. J Orthop Res 28(11):1411–1417

127. Shultz SJ, Schmitz RJ, Nguyen AD et al (2010) ACL research retreat v: an update on ACL injury risk and prevention, March 25–27, 2010, Greensboro, NC. J Athl Train 45(5):499–508
128. Shultz SJ, Schmitz RJ, Nguyen AD et al (2010) Joint laxity is related to lower extremity energetics during a drop jump landing. Med Sci Sports Exerc 42(4):771–780
129. Shultz SJ, Wideman L, Montgomery MM et al (2011) Some sex hormone profiles are consistent over time in normal menstruating women: implications for sports injury epidemiology. Br J Sports Med 45(9):735–742
130. Sigward SM, Powers CM (2007) Loading characteristics of females exhibiting excessive valgus moments during cutting. Clin Biomech (Bristol, Avon) 22(7):827–833
131. Sigward SM, Pollard CD, Cheng W-C et al (2010) The influence of sex and maturation on landing strategies: implications for ACL injury. J Athl Train 45(4):537–538
132. Simon RA, Everhart JS, Nagaraja HN et al (2010) A case–control study of anterior cruciate ligament volume, tibial plateau slopes and intercondylar notch dimensions in ACL-injured knees. J Biomech 43(9):1702–1707
133. Sinha-Hikim I, Taylor WE, Gonzalez-Cadavid NF et al (2004) Androgen receptor in human skeletal muscle and cultured muscle satellite cells: up-regulation by androgen treatment. J Clin Endocrinol Metab 89(10):5245–5255
134. Slauterbeck J, Clevenger C, Lundberg W et al (1999) Estrogen level alters the failure load of the rabbit anterior cruciate ligament. J Orthop Res 17(3): 405–408
135. Slauterbeck JR, Fuzie SF, Smith MP et al (2002) The menstrual cycle, sex hormones, and anterior cruciate ligament injury. J Athl Train 37(3):275–278
136. Slauterbeck JR, Hickox JR, Beynnon B et al (2006) Anterior cruciate ligament biology and its relationship to injury forces. Orthop Clin North Am 37(4):585–591
137. Stijak L, Herzog RF, Schai P (2008) Is there an influence of the tibial slope of the lateral condyle on the ACL lesion? A case–control study. Knee Surg Sports Traumatol Arthrosc 16(2):112–117
138. Strickland SM, Belknap TW, Turner SA et al (2003) Lack of hormonal influences on mechanical properties of sheep knee ligaments. Am J Sports Med 31(2):210–215
139. Swanik CB, Covassin T, Stearne DJ et al (2007) The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. Am J Sports Med 35(6):943–948
140. Sward P, Kostogiannis I, Roos H (2010) Risk factors for a contralateral anterior cruciate ligament injury. Knee Surg Sports Traumatol Arthrosc 18(3):277–291
141. Swartz EE, Decoster LC, Russell PJ et al (2005) Effects of developmental stage and sex on lower extremity kinematics and vertical ground reaction forces during landing. J Athl Train 40(1): 9–14
142. Trimble MH, Bishop MD, Buckley BD et al (2002) The relationship between clinical measurements of lower extremity posture and tibial translation. Clin Biomech (Bristol, Avon) 17(4):286–290
143. Uhorchak JM, Scoville CR, Williams GN et al (2003) Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 west point cadets. Am J Sports Med 31(6):831–842
144. Warden SJ, Saxon LK, Castillo AB et al (2006) Knee ligament mechanical properties are not influenced by estrogen or its receptors. Am J Physiol Endocrinol Metab 290(5):E1034–E1040
145. Wentorf FA, Sudoh K, Moses C et al (2006) The effects of estrogen on material and mechanical properties of the intra- and extra-articular knee structures. Am J Sports Med 34(12):1948–1952
146. Wiik A, Glenmark B, Ekman M et al (2003) Oestrogen receptor beta is expressed in adult human skeletal muscle both at the mrna and protein level. Acta Physiol Scand 179(4):381–387
147. Withrow TJ, Huston LJ, Wojtys EM et al (2006) The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. Am J Sports Med 34(2):269–274
148. Withrow TJ, Huston LJ, Wojtys EM et al (2006) The effect of an impulsive knee valgus moment on in vitro relative ACL strain during a simulated jump landing. Clin Biomech (Bristol, Avon) 21(9): 977–983
149. Wojtys EM, Huston L, Boynton MD et al (2002) The effect of the menstrual cycle on anterior cruciate ligament injuries in women as determined by hormone levels. Am J Sports Med 30(2):182–188
150. Woodford-Rogers B, Cyphert L, Denegar CR (1994) Risk factors for anterior cruciate ligament injury in high school and college athletes. J Athl Train 29(4):343–346
151. Woodhouse E, Schmale GA, Simonian P et al (2007) Reproductive hormone effects on strength of the rat anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 15(4):453–460
152. Wright RW, Dunn WR, Amendola A et al (2007) Risk of tearing the intact anterior cruciate ligament in the contralateral knee and rupturing the anterior cruciate ligament graft during the first 2 years after anterior cruciate ligament reconstruction: a prospective moon cohort study. Am J Sports Med 35(7):1131–1134
153. Yoo JH, Lim BO, Ha M et al (2010) A meta-analysis of the effect of neuromuscular training on the prevention of the anterior cruciate ligament injury in female athletes. Knee Surg Sports Traumatol Arthrosc 18(6):824–830
154. Yu B, McClure SB, Onate JA et al (2005) Age and gender effects on lower extremity kinematics of

youth soccer players in a stop-jump task. Am J Sports Med 33(9):1356–1364

155. Yu B, Garrett WE (2007) Mechanisms of non-contact ACL injuries. Br J Sports Med 41(Suppl 1): i47–i51
156. Yu B, Lin CF, Gross MT et al (2010) Simulated non-contact ACL injuries using a stochastic biomechanical model. J Athl Train 45(5):532
157. Yu WD, Liu SH, Hatch JD et al (1999) Effect of estrogen on cellular metabolism of the human anterior cruciate ligament. Clin Orthop Relat Res 366:229–238
158. Yu WD, Panossian V, Hatch JD et al (2001) Combined effects of estrogen and progesterone on the anterior cruciate ligament. Clin Orthop Relat Res 383:268–281

Index

F.R. Noyes, S.D. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
DOI 10.1007/978-3-642-32592-2, © Springer-Verlag Berlin Heidelberg 2012

B