ACL Injuries in the Female Athlete

Causes, Impacts, and Conditioning Programs

Frank R. Noyes
Sue Barber-Westin
Editors

Second Edition

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Preface

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

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

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

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

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

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

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

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Acronyms

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

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

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

Contents

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Part I

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

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

Frank R. Noyes and Sue Barber-Westin

Abstract

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

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1.1 Introduction

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

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

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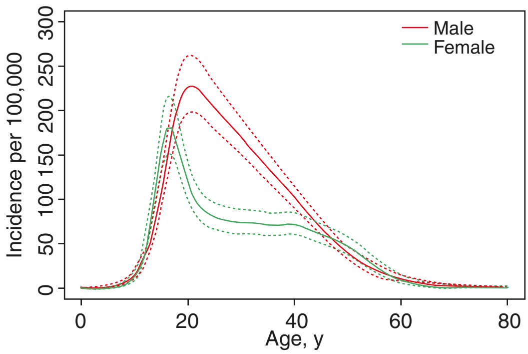

Fig. 1.1 Age-specific incidence of anterior cruciate ligament injuries in males and females (per 100,000 person-years) (Reprinted from Sanders TL, Maradit Kremers H, Bryan AJ, Larson DR, Dahm DL, Levy BA, Stuart MJ, Krych AJ (2016) Incidence of Anterior Cruciate Ligament Tears and Reconstruction: A 21-Year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

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

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

Critical Points

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

1.2 Anatomy

1.2.1 Overview

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

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

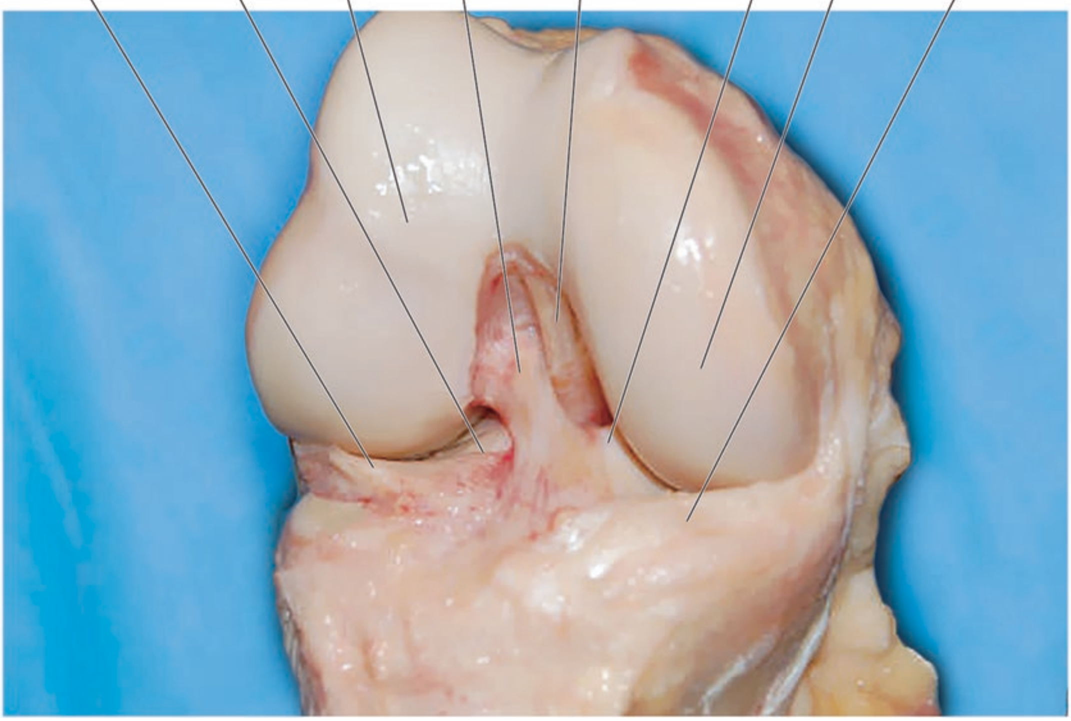

Fig. 1.2 Anterior view of the knee demonstrating the oblique orientation of the ACL originating on the medial aspect (side wall) of the lateral femoral condyle (Reprinted from Strickland J, Fester E, Noyes FR (2017) Lateral and posterior knee anatomy. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee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

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

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

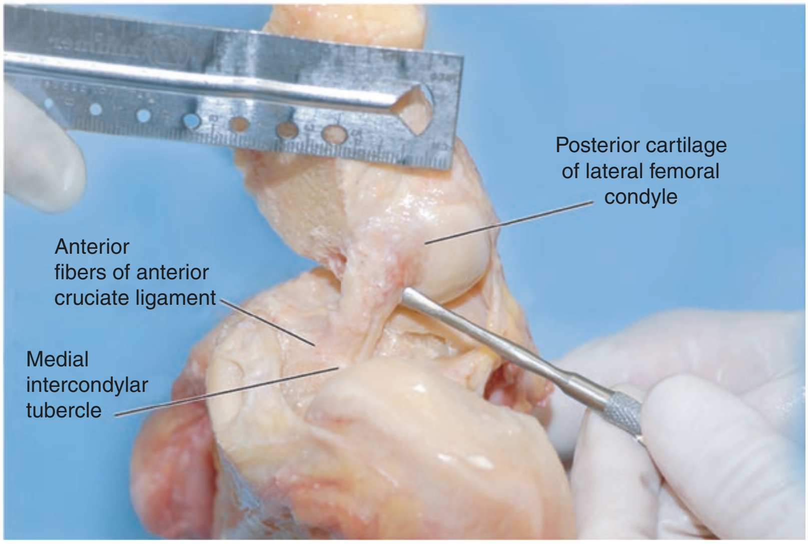

Fig. 1.3 Lateral view of the ACL. The anterior extension of the tibial insertion of the ACL is well visualized (Reprinted from Strickland J, Fester E, Noyes FR (2017) Lateral and posterior knee anatomy. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes.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

1.2.2 Division of ACL into Anteromedial and Posterolateral Bundles

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

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

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

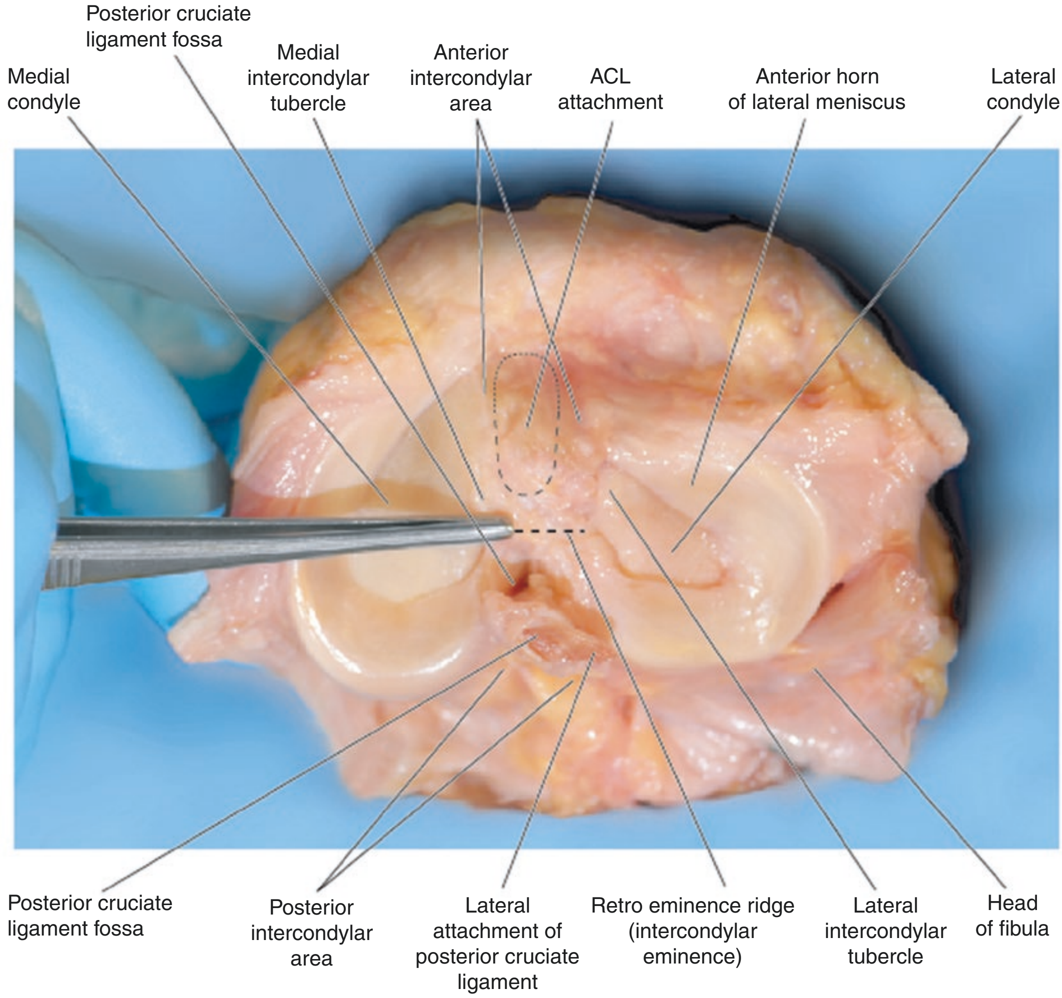

Fig. 1.4 Axial photo of the tibial plateau demonstrating the anterior insertion of the ACL. Notice the ACL's tibial insertion in relation to the medial tibial spine and the retro-eminence ridge (Reprinted from Strickland J, Fester E, Noyes FR (2017) Lateral and posterior knee anatomy. In: Noyes FR, Barber-Westin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

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

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

1.2.3 Gender Differences in ACL and Knee Joint Bony Anatomy

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

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

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

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

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

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

Critical Points

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

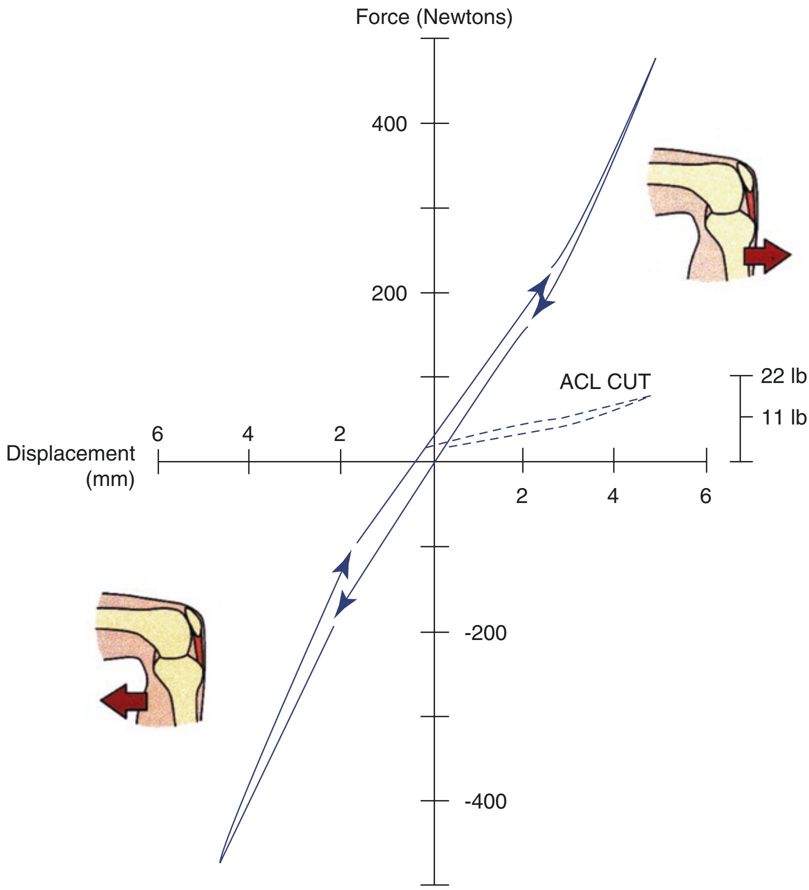

Fig. 1.5 A typical force-displacement curve for anterior-posterior drawer in an intact joint (*solid line*) and after cutting the ACL (*broken line*). The *arrows* indicate the direction of motion (Reprinted from Noyes FR, Grood ES (2017) Knee ligament function and failure. In: Noyes FR, Barber-Westin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

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

1.3 Biomechanics and Rotational Knee Stability

1.3.1 Primary and Secondary Function of the ACL

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

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

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

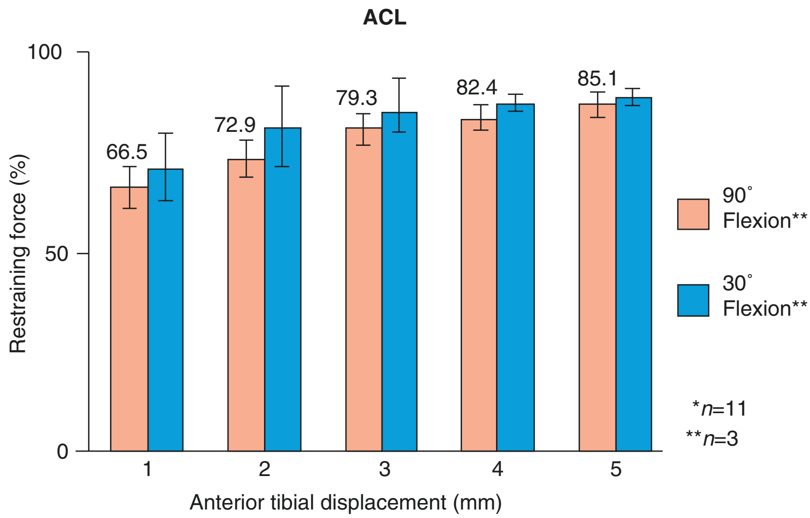

Fig. 1.6 Anterior drawer in neutral tibial rotation. The restraining force of the ACL is shown for increasing tibial displacements at 90° and 30° of knee flexion. The mean value is shown, plus or minus 1 standard error of the mean. Percentage values are given for 90° of flexion. No statistical difference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

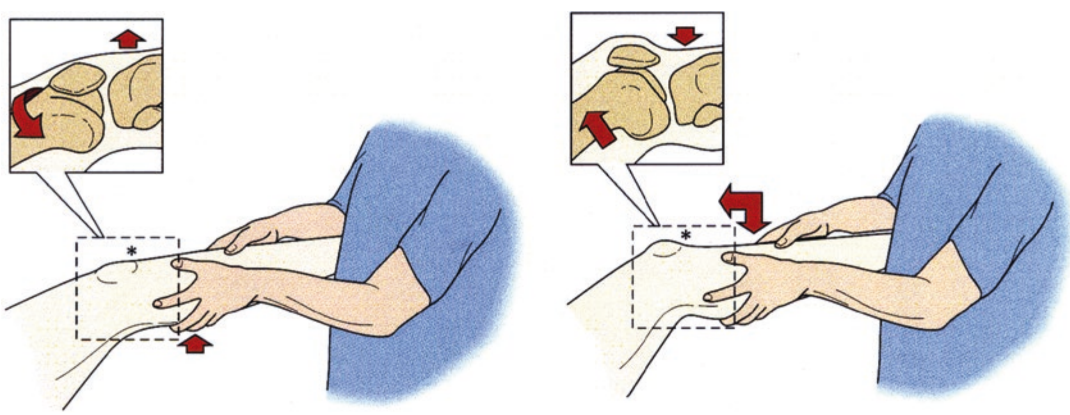

Fig. 1.7 *(Left)* Flexion-rotation drawer test, subluxated position. With the leg held in neutral rotation, the weight of the thigh causes the femur to drop back posteriorly and rotate externally, producing anterior subluxation of the lateral tibial plateau. *(Right)* Flexion-rotation drawer test, reduced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

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

1.3.2 Rotational Knee Stability

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

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

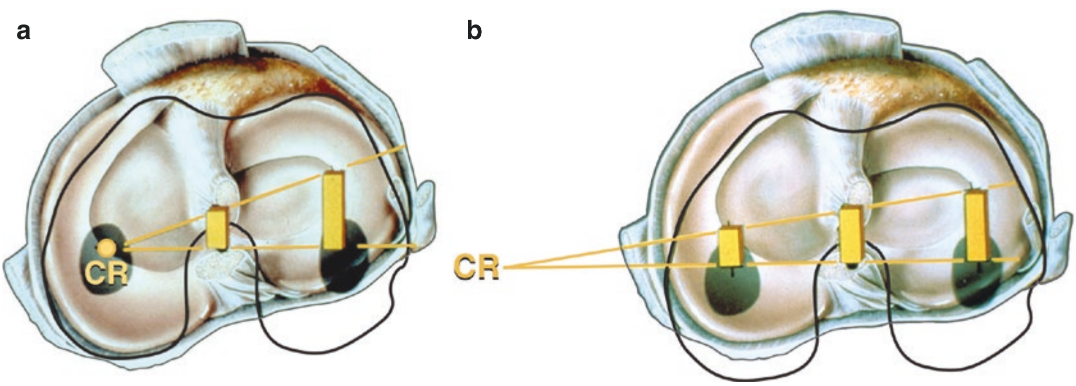

Fig. 1.8 Intact knee and after ACL sectioning: response to coupled motions of anterior tibial translation and internal tibial rotation. (**a**) Intact knee. The center of rotation (CR) may vary between the medial aspect of the posterior cruciate ligament and meniscus border, based on the loads applied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

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

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

1.3.3 Role of the Anterolateral Ligament Structures

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

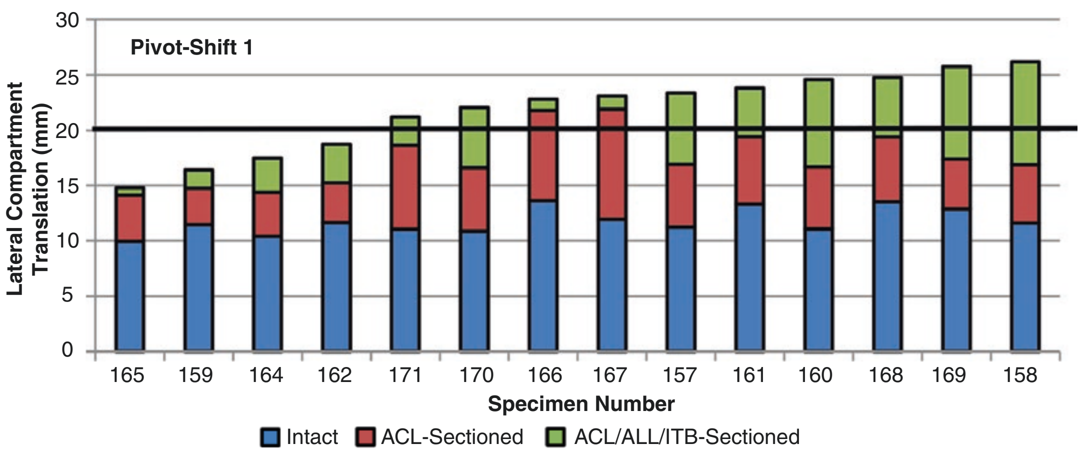

Fig. 1.9 Absolute lateral compartment translation of each specimen shown for intact, ACL-sectioned, and ACL-, ALL-, and ITB-sectioned states for pivot-shift 1 (100-N anterior force, 5-Nm internal rotation torque, and 7-Nm valgus). The bold line at 20 mm indicates the absolute magnitude of lateral compartment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

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

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

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

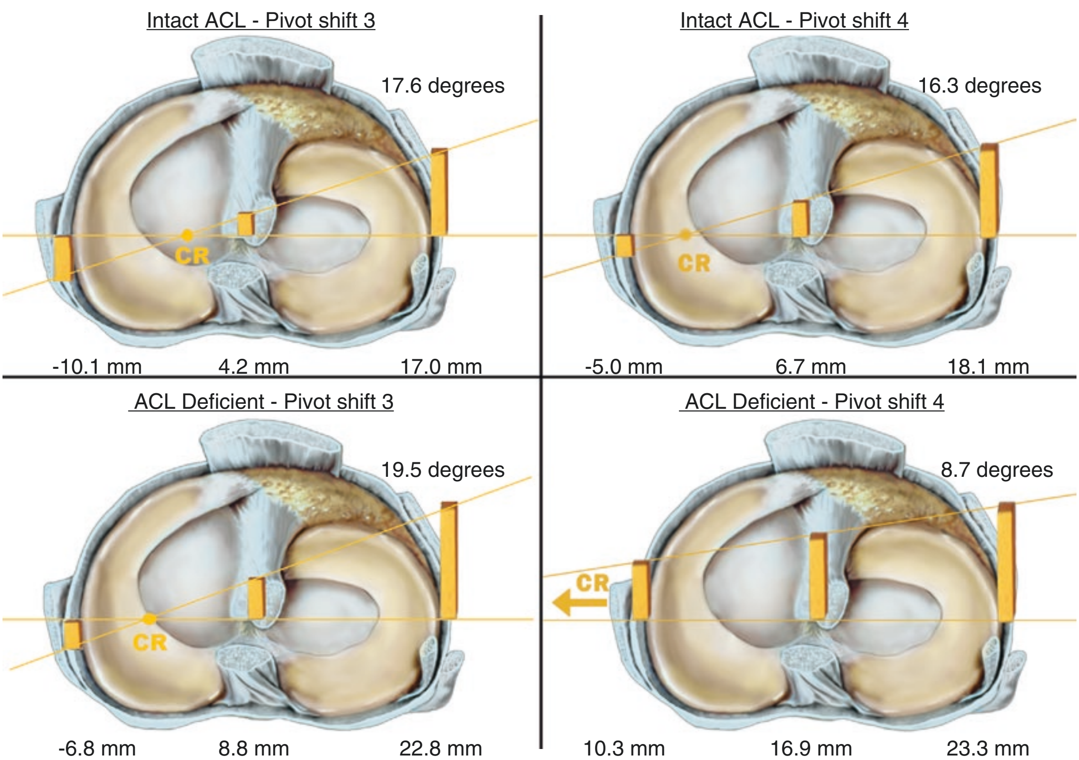

Fig. 1.10 A representative right knee specimen showing compartment translations and tibial rotation under two loading conditions: pivot-shift 3 and pivot-shift 4. In the pivot-shift 3 loading, there is a coupled internal rotation-valgus loading with a high internal rotation torque. There is no subluxation of the medial tibiofemoral compartment. In contrast, in the pivot-shift 4 loading, there is a coupled anterior tibial translation-internal rotation (low) and valgus loading. There is a medial shift in the center of tibial rotation, with subluxation of the medial, center, and lateral tibiofemoral compartments. Loading conditions for pivot-shift 3 were 35 N anterior, 5 Nm internal rotation, and 7 Nm valgus. Loading conditions for pivot-shift 4 were 100 N anterior, 1 Nm internal rotation, and 7 Nm valgus. *CR* center of tibial rotation (Reprinted from Noyes FR, Barber-Westin SD (2017) Anterior cruciate ligament primary reconstruction: diagnosis, operative techniques, and clinical outcomes. In: Noyes FR, Barber-Westin SD (eds) Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes. 2nd edn. Elsevier, Philadelphia, pp. 137–220)

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

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

Critical Points

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

1.4 Common ACL Injury Mechanisms

1.4.1 Current Proposed Mechanisms

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

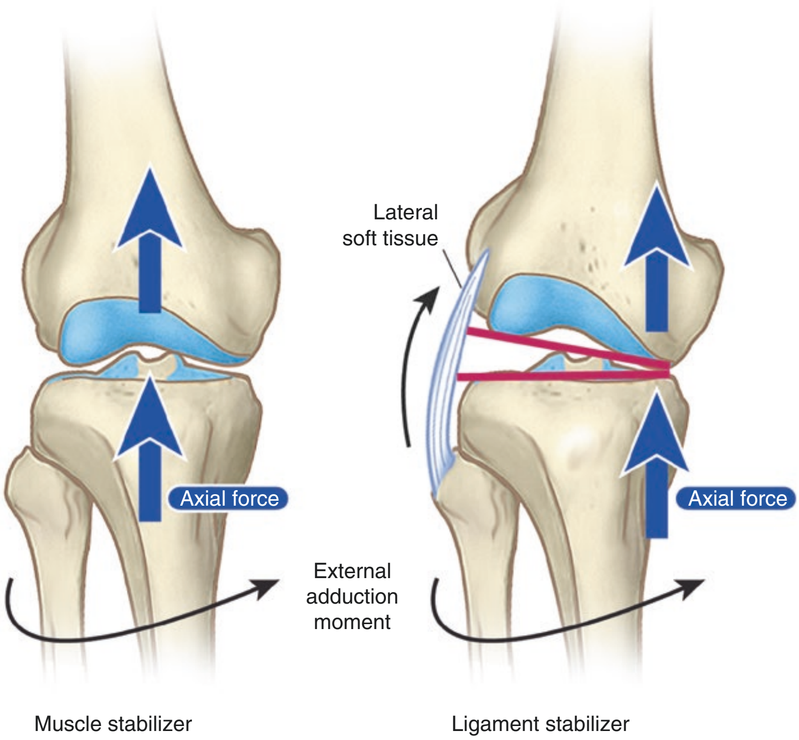

Fig. 1.11 *Left*, knee joint stability is influenced by the muscles, ligaments, and bony geometry, which act together to resist external adduction moments that are incurred during weight-bearing activities. *Right*, an abnormally high adduction moment may result in laxity of the lateral soft tissues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

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

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

The so-called quadriceps dominance mechanism for ACL injury is important. With the ath-