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INVITED REVIEW

Sports-Related Knee Injuries in Female Athletes

What Gives?

ABSTRACT

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Knee injuries occur commonly in sports, limiting field and practice time and performance level. Although injury etiology relates primarily to sports specific activity, female athletes are at higher risk of knee injury than their male counterparts in jumping and cutting sports. Particular pain syndromes such as anterior knee pain and injuries such as noncontact anterior cruciate ligament (ACL) injuries occur at a higher rate in female than male athletes at a similar level of competition. Anterior cruciate ligament injuries can be season or career ending, at times requiring costly surgery and rehabilitation. Beyond real-time pain and functional limitations, previous injury is implicated in knee osteoarthritis occurring later in life. Although anatomical parameters differ between and within the sexes, it is not likely this is the single reason for knee injury rate disparities. Clinicians and researchers have also studied the role of sex hormones and dynamic neuromuscular imbalances in female compared with male athletes in hopes of finding the causes for the increased rate of ACL injury. Understanding gender differences in knee injuries will lead to more effective prevention strategies for women athletes who currently suffer thousands of ACL tears annually. To meet the goal in sports medicine of safely returning an athlete to her sport, our evaluation, assessment, treatments and prevention strategies must reflect not only our knowledge of the structure and innervations of the knee but neuromuscular control in multiple planes and with multiple forces while at play.

Key Words: Anterior Cruciate Ligament, Athletic Injuries, Female, Biomechanics

INTRODUCTION

Girls and women are more active than ever in competitive athletics. Although the first Olympic event open to women was swimming in 1912, it would take six decades for passage of the education amendments of 1972, Title IX, and another 16 years for the 1988 Civil Rights Restoration Act, which reinforced compliance with Title IX. Title IX was enacted to level the playing field for women in athletics by mandating increased institutional support for women's programs. More recently, the United States women's world cup soccer champion team and the WNBA have provided venues for positive public support of women in athletics. Older women who may not have had access to competition at a younger age are getting the public health message about the health benefits of physical activity and taking advantage of available opportunities in sports.

As participation in sports continues to grow, the sports medicine clinician will treat female athletes presenting with knee pain and injury. Although female athletes experience similar injuries to men in comparable sports, there are some types of knee injuries that occur more frequently in women. It is paramount that physicians and other health care clinicians and researchers in the field of sports medicine determine the causative factors in this inequity as we continue to study maximization of sports functioning for our athletes. Gender differences in knee injury epidemiology, anatomy, neuromuscular control, and training and conditioning must be addressed in our didactic teaching about sports-related knee injuries so that healthcare providers can perform the best evaluation, physical assessment, and treatment planning. With increasing knowledge of causative factors in knee injuries, more effective and appropriate prevention strategies can be implemented for at risk individuals.

Knee: Form Follows Function, But Let's Not Forget Neurophysiology and Physics

Much of our undergraduate and medical school training revolves around understanding the articulations that make up the knee joint, the muscles and their attachments, and the neural structures innervating the knee's sensory and motor activities. Beyond learning the intricacies of the tibiofemoral joints and the patellofemoral joint, one cannot discuss the function of the knee without considering the proximal articulations (hip, pelvis, and spine) and distal articulations (ankle and foot) as knee function will depend upon and be dictated by the proximal and distal position of the lower limb and trunk. Similarly, one cannot ignore the proprioceptive function of receptors in multiple structures, including the anterior cruciate ligament (ACL) or quadriceps, and the alterations in proprioceptive function related to pain, edema or loss of continuity.

More fundamental is the acknowledgment that forces of gravity, momentum, and ground reaction in multiple planes of motion dictate sports-related knee function.[1] In no arena is this more pertinent than when one considers noncontact ACL injuries. Multiplanar control at the knee may be directly impacted by foot position, ligamentous laxity, muscle fatigue after repetitive eccentric contractions or knee joint positioning that inhibits rather than recruits the optimal muscle cocontraction patterns; therefore, all these areas are being studied in conjunction with the increase in noncontact ACL injuries in girls and women compared with boys and men.

This article will review the relevant literature in the area of knee injuries in women. After a brief review of anatomy, clinical and basic science research in the area of ACL injury will be reviewed along its various directions. Studies on hormonal effects on human ligament biomechanics evolved from animal studies. Studies of proprioception and balance in female athletes have developed from work on proprioception and balance in ACL-injured or ACL-deficient athletes. Studies of interventions to reduce injury risk are based on human biomechanical studies noting the differences in how males and females jump and land. Ongoing work includes interventional studies of neuromuscular training programs with elegant designs that one can use to direct prevention programs in the future in hopes of eliminating or at least reducing the higher injury rates in girls and women.

Knee Anatomy

The knee joint, the largest joint in the body, is comprised of three articulations: the patellofemoral and the medial and lateral tibiofemoral joints.[2,3] Knee movements are simplified primarily to flexion and extension however the knee is able to move in 6 *df*, including three translational and three rotational.[4] The medial and lateral menisci lie within the medial and lateral compartments, respectively. The meniscus act as shock absorbers and stabilize the knee by deepening the shallow tibial articular surfaces. Meniscal injuries commonly occur in the context of knee flexion, rotation and compression. Age-related mensical degeneration can cause friability of the meniscus predisposing to tears with minimal trauma.[5]

The medial (tibial) and lateral (fibular) collateral ligaments act to prevent valgus and varus movements of the knee as well as medial and lateral rotation. (Fig. 1) The medial collateral ligament (MCL) extends from the medial epicondyle of the femur to the medial condyle of the tibia, attaching to the medial meniscus. MCL injuries can occur in conjunction with acute medial meniscal tears. The lateral collateral ligament (LCL) extends from the lateral epicondyle of the femur to the fibular head. Posteriorly, the knee is protected by the oblique popliteal ligament, an extension of the semimembranosus muscle, and the arcuate popliteal ligament, which extends from the lateral condyle of the femur to the posterior aspect of the fibular head.

The cruciate ligaments, including the ACL and posterior cruciate ligament (PCL), prevent anterior and posterior translation of the knee joint. (Fig. 1) The ACL extends from the anterior intercondylar region of the tibia to the medial aspect of the

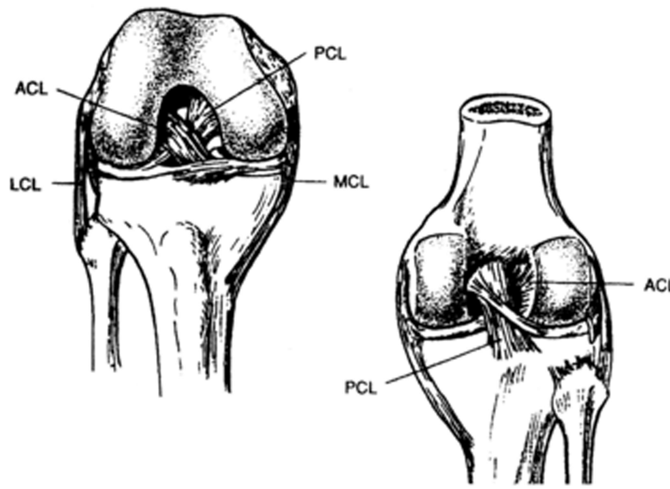

FIGURE 1 *Ligaments of the knee including Anterior Cruciate Ligament (ACL), Posterior Cruciate Ligament (PCL), Medial Collateral Ligament (MCL), and Lateral Collateral Ligament (LCL). Reprinted with permission from F. Fu and D. Stone, Sports Injuries: Mechanisms, Prevention, Treatment. Williams & Wilkins, 1994.*

lateral condyle of the femur. It prevents anterior displacement of the tibia, primarily in a flexed position, and hyperextension of the knee. The PCL extends from the posterior intercondylar region of the tibia to the lateral aspect of the medial condyle of the femur. It protects against hyperflexion of the knee joint and posterior translation of the tibia. The cruciate ligaments travel through the femoral notch.

The patella is part of the extensor mechanism of the knee, along with the quadriceps femoris muscle, quadriceps tendon and patellar tendon. The patella adds considerably to the stabilizing force of the extensor mechanism with patellofemoral joint reactive forces resulting when the patella is compressed against the femur.[6] Patellofemoral pain syndrome most typically presents because of chronic overload.[7] Increased femoral internal rotation can lead to abnormalities in tracking of the patella and is often caused by femoral anteversion, tight lateral thigh musculature, and weak gluteus medius.[8]

Multiple muscles act across the knee with long lever arms from the femur above and tibia below. These muscles are capable of generating and transferring considerable force to the knee. Ground reaction forces are transferred proximally via the weight-bearing knee to the hip and trunk; many sports require the unweighted lower limb to generate forces across the knee, as in kicking. Muscles about the knee regulate forces in the lower extremity and decelerate the body over the lower limb during running, landing, cutting, and stopping.[9] Primary muscles of knee control include the quadriceps anteriorly, the hamstrings (especially the semimembranosus), and gastrocnemius posteriorly, the gluteus medius and tensor fascia lata/iliotibial band laterally and the adductors medially. In sporting activities, the repetitive, eccentric nature of musculature activity about the knee may lead to fatigue related injuries.[10]

Epidemiology of Knee Injuries

The risk factors for lower extremity injuries have been divided into both extrinsic (from factors outside the body) and intrinsic (from factors within the body).[11,12] Extrinsic risk factors include level of competition, skill level, shoes and orthotic equipment, and playing surface. Intrinsic risk factors include age, sex, phase of the menstrual cycle, ligamentous laxity, previous injury, aerobic fitness, body size and limb girth, limb dominance, flexibility, muscle strength and imbalance, reaction time and postural stability, anatomic alignment and foot morphology. Although the focus of this paper is on gender differences, risk factors will be discussed in regards to sex hormones/menstrual cycle, anatomic considerations, and neuromuscular imbalances. See Table 1 for an overview of these topics and references. It may be that the salient risk factors for sports-related knee injury differs between men and women.

Gender as a Risk Factor

In regards to gender difference, many studies have shown that female athletes sustain more knee injuries than male athletes, specifically ACL sprains.[13–18] Anterior knee pain is more common in women athletes than men.[19] In one study of male and female professional basketball players evaluated by their athletic trainers, females suffered 60% more injuries than males, with knee and

TABLE 1 Risk factor for knee injury in female athletes

Risk Factor for Knee Injury	Reference
Female Gender	
NCAA injury rates differ, female > male	Arendt et al.[13]
High school injury rates differ, female > male	Chandy et al.[15] Powell et al.[14] Zillmer et al.[18]
Professional basketball injury rates differ, female > male	Zelisko et al.[17]
Sex Hormones	
Injury rate differs by menstrual cycle phase	Myklebust et al.[23] Wojtys et al.[24] Slauterbeck et al.[25]
No variation in ligament laxity in different phases	Belanger et al.[29]
Oral contraceptive use offered no injury protection	Arendt et al.[26]
Anatomic Considerations	
Q angle higher in injured female athletes	Shambaugh et al.[31]
Static postural faults correlated with higher injury rate	Loudon et al.[33]
Femoral notch parameters associated with injury (consensus paper)	Griffin et al.[20]
Notch size associated with increased injury risk	Shelbourne et al.[41]
Notch size not associated with increased injury risk	Schickendantz et al.[42] Teitz et al.[43]
Notch shape associated with increased injury risk	Ireland[44]
Neuromuscular Imbalances	
Proprioception deficits in ACL-deficient or ACL-injured	Barrack et al.[45] Wojtys et al.[46] Barrett et al.[47] Corrigan et al.[48]
Single leg stance deficits females > males	Hewett et al.[51,52]
Jumping and landing strategies differ female *vs.* male	Schultz et al.[53] Rozzi et al.[54]
Jump landing did not differ female *vs.* male	Fagenbaum et al.[64]
Females with greater valgus dominant knee	Ford et al.[57]
Females with highly dominant dominant leg	Hewett et al.[59]
Preseason strength and conditioning deficits associated with injury	Knapik et al.[60]
Preseason conditioning program associated with reduced injury	Hewett et al.[68] Caraffa et al.[69]
Quadriceps-dominant pattern in female athletes	Huston et al.[36]
Quadriceps-dominant pattern in elite athletes	Baratta et al.[63]
Eccentric muscle fatigue in female athletes	Nyland et al.[70]
Stiffness/elasticity differences females *vs.* males	Winter et al.[74]

thigh injuries most common.[17] In a study of female secondary school basketball players, injuries to the knee accounted for 91% of season ending injuries and 94% of injuries requiring surgery.[15] It is estimated that 1 in 3,000 individuals in the United States sustains an ACL injury, accounting for 100,000 injuries annually, with women at higher risk in particular sports.[20] Researchers have calculated that in 2002 there were approximately 7,000 ACL ruptures in high school female basketball players alone, using an injury rate of 1 per 65 participants, and 452,728 female high school basketball players in the United States.[18,21] The relationship between gender and increased rate of ACL tears has been well documented; however, the relationship between gender and other lower extremity injury is less clear.[22]

Sex Hormones and Menstrual Cycle Considerations

Fluctuation in sex hormones during the menstrual cycle has been studied as a risk factor for ACL tears in female athletes with varying results, implicating both the follicular and ovulatory phase as times of highest risk.[23–25] There are methodological issues that may explain the variability in findings, with many studies relying on athlete self-report of menstrual cycle phase at the time of the injury. A recent study that measured hormone metabolites in urine, to determine both menstrual phase at the time of injury and cycle length, showed poor correlation of urine metabolite based determination of menstrual phase with self-report of menstrual phase.[24]

The menstrual cycle is generally divided into three phases—follicular, ovulatory, and luteal—with some researchers further dividing luteal into early and late luteal phase. However, there are differences in the number of days defined in each phase between studies. This variable time interval for defining cycle length can directly impact the study findings, adding to the confusion. In addition, some athletes take oral contraceptive pills, which may introduce another bias if exogenous hormones act differently than endogenous hormones. In a review of college varsity athletes sustaining noncontact ACL injuries, oral contraceptive use did not protect against injury.[26] This topic needs further elucidation.

Finally, the mechanism of action of the sex hormones to increase the rate of ACL tears remains to be elucidated. Estrogen and progesterone receptors have been found on the rabbit ACL.[27,28] This finding implies that sex hormones may influence the structure and function of the human ACL, perhaps compromising load bearing and proprioceptive feedback, however this has not been proven in human studies. A recent study of knee laxity throughout the menstrual cycle, using waking temperature and self-report of menstruation to define menstrual cycle phase and the KT-2000 arthometer (Medmetric Corp, San Diego, Calif) to measure knee laxity, demonstrated that knee laxity did not vary with menstrual phase, either before or after acute bouts of exercise.[29] Further study of the role of human reproductive hormones and ACL injury is warranted.

Anatomic Considerations in Knee Injury

Various studies have considered anatomic determinants of the knee and their role in the higher knee injury rates in women, but none have directly correlated anatomy with causing the increased incidence of noncontact ACL tears in women. The Q-angle (quadriceps angle) is defined as the angle between the line connecting the anterior superior iliac spine and the midpoint of the patella, and the line connecting the tibial tubercle and the same reference point of the patella.[30] Recreational basketball players who suffered knee injuries were found to have a higher Q-angle than noninjured players.[31] A review of the literature on Q-angles measurements concluded that this measure is of limited value overall in individuals presenting with anterior knee pain.[32] The miserable malignment syndrome, including pronation of the feet, increased femoral anteversion, and increased genu valgus, was thought to be contributory to anterior knee pain in women, but no studies have documented this finding. Static postural faults, studied with stepwise logistic regression, showed that the factors demonstrating statistically significant differences between the ACL-injured female athletes and age-matched controls included excessive navicular drop, knee recurvatum and excessive subtalar joint pronation.[33] Although studies have shown that women are more likely to have joint laxity, this has not been directly correlated to the higher knee injury rate seen in women.[34–36]

Numerous studies have been done to determine the relationship between the size and shape of the femoral notch and ACL injury rate.[37–41] The notch width index, the width of the anterior outlet of the notch divided by the total notch width at the level of the popliteal groove, is the measurement used frequently in studies of ACL injuries. It has been compared side to side and in injured *vs.* noninjured athletes, with conflicting findings regarding its association with ACL injury rate.[42,43] The shape of the intercondylar notch has been studied, with A-shaped notches associated with increased injury rates and perhaps related to a smaller ACL.[44] Published findings from a symposium on ACL tears in female athletes concluded that notch dimensions and ACL injury seem to be associated with injury, but that this association was not proven to be causal.[20] The expert panel did not see a role for prophylactic notchplasty to widen the femoral notch in a patient's uninjured knee.

The Role of Dynamic Neuromuscular Imbalances and Knee Injury

Dynamic control of the knee is an area of research related to ACL tears in women that continues to grow. Proprioception and reaction time, postural stability, limb dominance, muscle stiffness and firing patterns, and landing biomechanics are all being studied in hopes of elucidating risk factors for knee injury in women, specifically noncontact ACL tears. This line of research stems from previous work looking at ACL-deficient or ACL-injured subjects and their neuromuscular patterns to infer what factors may be related to ACL injuries.

The ACL has been studied in injured athletes both with and without ACL reconstruction. Numerous studies of proprioceptive capacity in ACL-deficient athletes demonstrate deficits in the involved limb compared with uninvolved.[45–49] In the postreconstruction group that continues to have an unstable knee despite findings of mechanical stability on ligamentous measurements, the remaining instability is presumed to be related to proprioceptive deficits. There are multiple measures to assess proprioception and neuromuscular control at the knee employed in the literature, including (1) Testing joint position sense by setting the subject's limb at a predetermined angle, then asking the subject to reproduce this angle; (2) Testing threshold to perception of passive movement; (3) Testing muscular activation and latency of reflex contraction after force application; and (4) Testing standing balance with stabilometry.[50] Female athletes are being tested compared with males to look for differences in proprioception and neuromuscular control at the knee that might increase their risk of injury.

One possibility for the higher incidence of knee injury in women compared with men may be a disparity in knee proprioceptive and neuromuscular control in female athletes.[51] Single leg stance stability was better in female control subjects than in males; however, in subjects with ACL deficiency, males had significantly more single leg stability than females, both pre- and postoperatively, and the deficit in single leg stance perpetuated longer postoperatively in females.[52]

Studies have shown that women run, land, and jump differently than men when playing sports.[53,54] The usual mechanism for noncontact ACL tears involves a deceleration before change of direction or landing with the knee between full extension and 20 degrees of flexion.[55,56] Therefore, the differences in landing and other movement strategies between male and female athletes have the potential to explain at least some of the disparity in noncontact ACL injury rates. Male and female high school basketball players were studied with three dimensional motion analyses while landing a drop vertical jump and preparing to immediately perform a maximum vertical jump.[57] Female athletes landed with greater maximal valgus angle and with significant differences between their dominant and nondominant knees, compared with males.

Neuromuscular Patterns: Ligament, Leg and Quadriceps Dominance

Subjects with high valgus moments at the knee have been referred to as ligament dominant.[58] The inability of the leg musculature to control motion results in high strains across the ACL as it acts to limit valgus force. Women have also been found to have a highly dominant leg, with significant side-to-side strength and flexibility deficits noted.[59] This mismatch may lead to a higher incidence of ACL injury to the dominant knee, as it preferentially works to limit the forces of gravity, or a higher risk of injury to the nondominant knee, as it is significantly weaker and less able to manage such forces. This leg dominance as a possible factor in ACL injury in women has been studied in conjunction with side-to-side differences, not only in valgus loading, but with preseason strength, flexibility, and coordination deficits correlating with injury rate.[60]

Quadriceps dominance is another pattern of neuromuscular control that may be associated with ACL injury. In a laboratory study, anterior tibial translation applied to the limbs of female and male athletes was met by different strategies, with females initially firing their quadriceps, and males and untrained females initially firing their hamstrings to counter the load.[36] This has been described as a quadriceps-dominant pattern in female athletes. Quadriceps contraction without cocontraction of the hamstrings can lead to greater loading of the ACL.[61] Hamstring cocontraction acts synergistically with the ACL, decreasing anterior and rotatory displacement of the tibia from 15° to 80° of knee flexion.[62] In a laboratory study using EMG during isokinetic testing, elite athletes with hypertrophied quadriceps had less cocontraction of their hamstrings than recreational athletes or nonathletes.[63] Hamstring activation during leg extension was proposed as a stabilizer of the knee, and serves as the basis for ACL prevention programs that teach motor control with greater knee flexion to activate the hamstrings. A controlled laboratory study of eight female and six male college varsity basketball players failed to show a significant difference in knee muscle activation patterns, with females landing with greater knee flexion and demonstrating time to peak force measures similar to their male counterparts, and contrary to previous studies.[64] It is not clear whether this particular group of female athletes had been previously trained to land with greater knee flexion in their preseason training program. The hamstring/quadriceps ratio has been used historically for assessment of muscle balance using concentric values (Hcon/Qcon) for both muscle groups. However, to describe physiologic function about the knee joint, the hamstring/quadriceps ratio should be calculated using Hecc/Qcon for knee extension, and Hcon/Qecc for knee flexion.[65] This change to a more functional H/Q ratio has implications for ACL research studies and for prevention and rehabilitation programs.

Muscle Strength And Knee Stiffness

Women have less quadriceps and hamstring strength than men, even after normalizing for body weight.[66,67] Conditioning exercises have imparted some protection against injury.[68,69] In a study of 20 healthy athletic women, fatigue from eccentric quadriceps femoris exercise, but not eccentric hamstring exercise, produced delayed onset of vastus medialis, rectus femoris and vastus lateralis firing during crossover cutting training.[70] The gastrocnemius muscle fired earlier with quadriceps fatigue, presumably to aid in dynamic knee stabilization. The authors argue that gastrocnemius training in knee rehabilitation and training programs for female athletes is necessary. Several authors have also studied knee stiffness, or muscle contractility across the knee joint that acts to dissipate forces across ligaments, and have found gender differences, although others have not.[51,71] Stiffness is regulated in part by mechanoreceptors in the knee ligaments and capsule that influence muscle spindle afferents from agonist and antagonist muscles.[72,73] Training may impact these responses. Other intrinsic factors that play a role in muscle stiffness, such as musculotendinous elasticity, may not be amenable to training.[74]

Prevention Strategies

The identification of neuromuscular imbalances in women forms the basis for ACL injury prevention training interventions. Recommendations include training to counter dominant-leg dominance, ligament dominance, and quadriceps dominance in women. Many researchers feel that specific training programs may lessen the risk of noncontact ACL tears in females. For instance, recommendations for hamstring training were made by researchers who noted quadriceps-dominant muscle activation patterns on EMG testing, or in response to anterior tibial translation.[36,63] Strength training is also recommended, given the gender differences in hamstring and quadriceps strength.

More recently, prospective studies of exercise interventions have been completed. An exercise intervention study demonstrated that a progressive five-phase balance board training program decreased the incidence of ACL injury by 7-fold in high level male soccer players.[69] In a study of elite female handball players, an ACL injury prevention program with 3 different sets of exercises performed three times a week during a training period of 5–7 wk, and then once a week during the season, resulted in improved dynamic, but not static, balance.[75] Eleven female athletes trained with a three-phase jump training program and demonstrated increased knee flexion with landing, reduced knee adductor and abductor moments at the knee, increased strength of the hamstrings muscles, and limited peak landing force by 22%.[59] This type of plyometric training resulted in reduced rates of injury in trained *vs.* untrained female athletes studied prospectively through high school volleyball, soccer, and basketball seasons.[68]

In recognition of the running, jumping, and landing differences between genders, recommendations have been made that athletes avoid high-risk positions such as landing on one limb or with knee extension.[76] The focus for coaching interventions is to teach performance in a safety position: flexed hips and knees, avoiding adduction and internal rotation of the femur and external tibial rotation.[77] (Fig. 2) There have been no studies documenting the success of this type of coaching intervention.

Identifying individuals at risk may be another means of reducing ACL injury rate. In preparticipation screening of just over 2700 high school athletes, musculoskeletal problems were the leading cause of restriction from sports activity, and the second leading cause for recommended follow-up.[78] It may be that preparticipation screening could be used to identify dynamic neuromuscular imbalances that place girls and women at risk of knee injury. Further study in this area is needed. It may be necessary for female athletes to show proficiency in strength, flexibility, and advanced motor skills required for cutting and jumping sports to participate.[79]

Current Recommendations and Future Directions

The literature reviewed in this article demonstrates that girls and women are at greater risk of knee injuries, especially in cutting and jumping

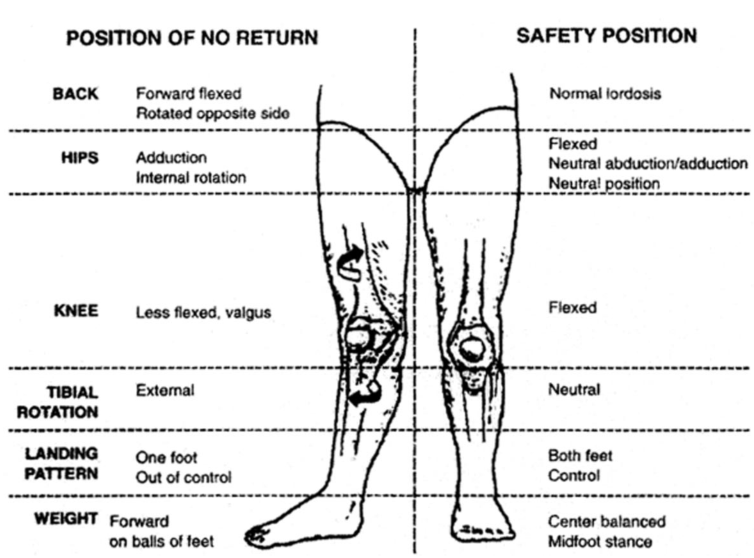

FIGURE 2 *The position-of-no-return mechanism for ACL injury and the safe position. Reprinted with permission from Ireland ML, Anterior Cruciate Ligament Injury in Female Athletes: Epidemiology.* J Athlet Train *1999; 34:150–154, NATA.*

sports, than boys and men in similar sports. A number of variables that affect ACL injury rate are being considered, none of which likely works in isolation. To solve this serious problem of noncontact ACL injuries, basic science and clinical researchers are working together with clinicians and team personnel in hopes of bringing the latest information to female athletes in the field. This will allow for in vivo testing of exercise interventions and additional prospective studies of hormones, anatomical variables, and dynamic neuromuscular imbalances to eliminate this mismatch in injury rate.

In the interim, the current studies should be used to direct us in an evidence-based approach to care and prevention. Female athletes should be screened for neuromuscular imbalances in the preparticipation physical examination. Ideally, jumping and landing techniques should be observed, with specific recommendations made when dangerous behaviors are observed, such as landing on an extended knee. Training programs should include plyometric activities that train the lower limb in multiple planes of movement, incorporating acceleration and deceleration. The goal of training is for each female athlete to develop a repertoire of movement patterns to deal effectively with the forces of gravity and momentum, allowing for quick, coordinated cocontraction of muscles about the lower limb, pelvis, and trunk to avoid overload of the ACL and patellofemoral joint.

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