Clinical Sports Medicine Update

Anterior Cruciate Ligament Injuries in Female Athletes

Part 1, Mechanisms and Risk Factors

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The mechanism underlying gender disparity in anterior cruciate ligament injury risk is likely multifactorial in nature. Several theories have been proposed to explain the mechanisms underlying the gender difference in anterior cruciate ligament injury rates. These theories include the intrinsic variables of anatomical, hormonal, neuromuscular, and biomechanical differences between genders and extrinsic variables. Identification of both extrinsic and intrinsic risk factors associated with the anterior cruciate ligament injury mechanism may provide direction for targeted prophylactic treatment to high-risk individuals.

Keywords: anterior cruciate ligament (ACL); injury mechanisms; biomechanics; female athlete

ACL INJURY EPIDEMIOLOGY IN FEMALE ATHLETES

Anterior cruciate ligament injury occurs with a 4- to 6-fold greater incidence in female athletes compared with male athletes playing the same landing and cutting sports.[2] The elevated risk of ACL injury in women, coupled with the 10-fold increase in high school and 5-fold increase in collegiate sport participation in the past 30 years, has led to a rapid rise in ACL injuries in female athletes.[80,81] This increase in ACL injury in the female sports population has fueled intense examination of the mechanisms responsible for the gender disparity in these debilitating sports injuries.[§] Rupture of the ACL is costly, with conservative estimates of surgery and rehabilitation at $17 000 to $25 000 per injury.[23,41] This cost is in addition to potential loss of entire seasons of sports participation, loss of scholarship funding, lowered academic performance, long-term disability, and significantly greater risk of radiographically diagnosed osteoarthritis.[34,91]

The mechanism underlying gender disparity in ACL injury risk is likely multifactorial in nature. Several theories have been proposed to explain the mechanisms underlying the gender difference in ACL injury rates. These theories include related extrinsic (physical and visual perturbations, bracing, and shoe-surface interaction) and intrinsic (anatomical, hormonal, neuromuscular, and biomechanical differences between genders) variables. Identification of both extrinsic and intrinsic risk factors associated with the ACL injury mechanism provides direction for targeted prophylactic treatment to high-risk individuals.

EXTRINSIC MECHANISMS OF INJURY

Contact With Another Player Versus Noncontact ACL Injuries

McNair et al[74] reported that 70% of ACL injuries are noncontact and 30% are contact injuries. Boden et al[14] interviewed athletes regarding the mechanisms of their ACL injuries using a questionnaire. A noncontact mechanism was reported in 72% and a contact injury in 28% of the cases. There is relative consensus in the literature that approximately 70% of ACL injuries are noncontact in nature. However, the specific definition of a noncontact ACL injury varies from study to study. The definition used by Myklebust et al[78,79] is specific. Their definition of a noncontact ACL injury is an injury that occurs in the absence of player-to-player (body-to-body) contact. The Olsen et al[85] definition of contact injury is also specific in terming an ACL injury that occurs as the result of a direct blow to the knee a "contact." Those situations in which there is an ACL injury with no direct blow to the knee but body-to-body contact are difficult to classify. We term these injuries noncontact ACL injury with perturbation.

Boden et al[14] also used a questionnaire to determine that most of the examined ACL injuries were sustained at foot

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strike with the knee close to full extension. Video analyses of 27 separate ACL disruptions confirmed that most noncontact injuries occurred with the knee close to extension during a sharp deceleration or landing maneuver.[14] Olsen et al[85] performed a videographic examination of ACL injury mechanisms in team handball. They concluded that the ACL injury mechanism in women was a forceful valgus collapse with the knee close to full extension combined with tibial rotation. These analyses demonstrate some consistent mechanisms, including valgus, extended knee, and widened stance; however, they also highlight the difficulty of determination of the exact mechanism of injury from eyewitness account or even slow-motion video.

Motion Perturbations

Olsen et al[85] reported that ACL-injured Norwegian team handball players were often judged by the coaches to be out of balance, and in the majority of cases, some form of perturbation (often contact with another player) occurred that appeared to alter the player's coordination or movement. All players were handling the ball when injured, and they had taken 0 to 3 steps with the ball before being injured.[85] McLean et al[72] examined the effect of gender and the presence of an opponent (a laboratory skeleton) on the biomechanics of sidestep cutting. Women had increased valgus and foot pronation angles and greater variability in knee valgus and tibial internal rotation during cutting. Women also had less hip and knee flexion and hip abduction during cutting, although the mechanisms for these differences were unclear. Gender differences in the joint kinematics suggest that increased dynamic lower extremity valgus contributes to ACL injury risk in women and that the hip and ankle play an important role in controlling valgus during sidestepping. Perturbations likely play a role in the mechanism of some ACL injuries, as they do appear to be involved during videographic and biomechanical analyses.

The Effects of Bracing

It is unknown whether prophylactic bracing can decrease the risk of ACL injury. Boden et al,[14] in a small retrospective cohort of ACL injuries, found that only 2% of ACL injuries occurred while the leg was braced. Wojtys et al[121] assessed the effect of 6 different brace designs on anterior tibial translation and neuromuscular function of chronically unstable patients with ACL deficieny. Bracing decreased anterior tibial translation 29% to 39% without the stabilizing contractions of the hamstring, quadriceps, or gastrocnemius muscles. With muscle activation and bracing, anterior tibial translation decreased between 70% and 85%. However, the braces appeared to consistently slow hamstring muscle reaction times. Yu et al[123] showed that a brace with a 5° extension stop decreased extension on landing.

It is unknown whether functional bracing (postreconstruction) decreases risk of graft reinjury. Few studies have examined the effect of functional bracing on ACL injury risk. Wu et al[122] found that knee bracing did not improve functional performance of subjects after ACL reconstruction and concluded that bracing could actually slow down running and turning. McDevitt et al[70] also studied functional bracing after ACL reconstruction. Groups were randomized into braced or nonbraced groups. The braced group was instructed to wear a functional knee brace for all cutting, pivoting, or jumping activities for the first year after ACL reconstruction. There were no differences between groups in knee stability, functional testing, subjective knee scores, and range of motion or strength testing. They concluded that postoperative bracing did not change outcomes. There are insufficient data at this time to determine if functional bracing decreases the risk of ACL injury or reinjury. The preponderance of the data indicates that the current brace designs cannot prevent injury.

Shoe-Surface Interaction

Scranton et al[97] monitored noncontact ACL injuries in the National Football League over 5 seasons and examined the relationship of the variables of playing surface, shoe type, and playing conditions to the occurrence of these injuries. More ACL injuries occurred on natural grass than on an artificial surface. Almost half of all injuries (47.5%) occurred during game-day exposures, despite the fact that the practice versus game-day exposure rate was 5:1. More than 95% of ACL injuries occurred on a dry field.[97] Orchard and Powell[86] examined the relationship between knee and ankle sprains, playing surface, and the weather conditions on the day of the game. They reported a reduced risk of significant knee sprains on grass compared with indoor synthetic (plastic resin) turf. They found that cold weather was associated with a lower risk of significant knee sprains and ACL injuries when compared with hot weather in outdoor stadiums. The authors concluded that cold weather was associated with lower ACL injury risk in outdoor grass stadiums related to the reduced shoe-surface traction.[86] Olsen et al[85] provided a videographic examination of injury mechanisms for ACL injuries in team handball. They found more ACL injuries occurred on synthetic, rubberized indoor floors than on wooden floors. However, Baker[4] concluded from a review of the literature that there was no strong association between playing surface or footwear and ACL injury risk. Although the available data on shoe-surface interaction have not led to a consensus on its relation to ACL injury risk, biomechanical examination of this possible mechanism should be studied further as it is an area with high potential for intervention (Figure 1).

INTRINSIC MECHANISMS TO INJURY

Anatomical

Anthropometric Differences. A number of studies of ACL injury risk factors have focused on anatomical or anthropometric measures such as tibia length and thigh length and height.[11,113] Beynnon et al[11] reported that increased thigh length was an injury risk factor in female skiers.[9] Lower extremity bone lengths may underlie increased risk of ACL injuries; however, anatomical measures often do not correlate with dynamic injury mechanisms.[77]

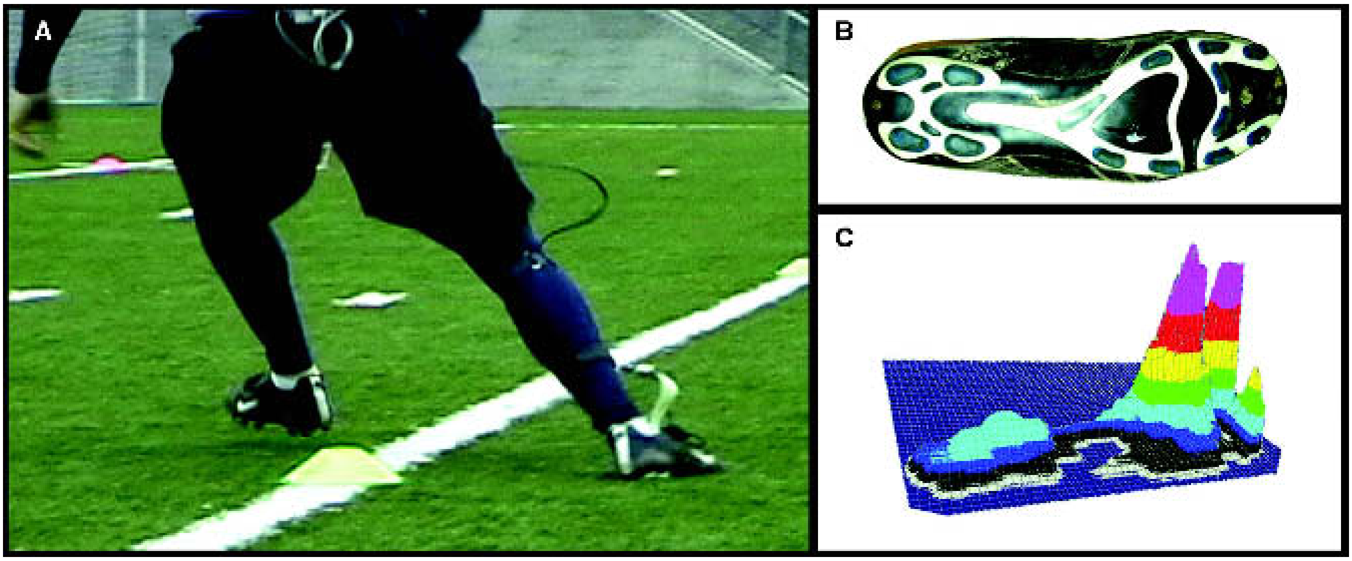

Figure 1. Foot-shoe-ground interfaces. A, examination of extrinsic ACL mechanism should investigate dynamic movements that mimic ACL injuries, such as a rapid deceleration and change of direction on different surfaces. Example of cleat design (B) and Pedar (C) in shoe pressure distribution during a cutting maneuver on artificial turf.

Anatomical measures are difficult to modify by nature; therefore, the potential impact of research into these mechanisms is relatively small.

Static Alignment: Increased Q Angle/Pelvis Width. Another anatomical hypothesis is related to the Q angle.[39,125] Women have a relatively wider or differently shaped pelvis that could lead to an increased Q angle, and this increased angle could relate to increased injury rates.[39,125] In contrast, others have reported that injury rate differences were not related to anatomical differences such as Q angle. Static Q angle measures do not appear to be predictive of either knee valgus or ACL injury risk during dynamic movement, thus supporting further exploration of other dynamic neuromuscular factors and their role in limb alignment during landing and cutting.[37,77]

Decreased Notch Width. Another structural hypothesis that addresses ACL injuries specifically is that female athletes have smaller femoral notch widths, relative to the size of the ACL, than do male athletes. Emerson[27] and others[100] have hypothesized that a narrow intercondylar notch predisposes the female knee to ACL injury, perhaps because a narrower notch leads to a smaller, weaker ACL. The ACL is positioned within the notch, and a narrow notch could cause increased elongation of the ACL under high tension. Uhorchak et al[113] reported that women with a narrow intercondylar notch (< 13 mm) had a 16.8 times greater risk ratio than did those with a larger notch width. Shelbourne et al[100] stated that a small notch is associated with a small ACL and that gender is not the factor—it is just that more women than men have small notches. Other reports show no difference in notch width normalized to bone width in female and male athletes or an association between notch width and injury.[2,43,47,54]

Increased General Joint Laxity. The female athlete has increased general joint laxity relative to her male counterpart.[14,103] Boden et al[14] reported that ACL-injured patients demonstrated significantly more knee recurvatum at 10° and 90° of hip flexion and an increased ability to touch palms to floor. Generalized joint laxity and hyperextension were found to significantly increase the risk for injury in female soccer players.[103] Uhorchak et al[113] reported that women with generalized joint laxity had a 2.7 times greater risk of ACL injury than did those without laxity. Joint laxity affects not only sagittal knee motion (hyperextension) but also coronal knee motion (valgus), which can strain the ACL and be related to increased risk in female athletes.[14,43,65,66,113]

Increased Muscle (Hamstrings) Flexibility. Boden et al[14] reported that the hamstrings muscles were significantly more lax in ACL-injured athletes compared with matched controls. Female and male flexibility patterns diverge during and after puberty. Flexibility decreases with chronological age and maturational stage in boys, whereas girls show increases after puberty. For example, the sit-and-reach test (a measure of the flexibility of the lower back, hip, and upper thigh) scores decrease steadily in boys, whereas scores increase in girls.[63] During and after puberty, coincident with dramatic increases in height and weight, boys have a significant decrease in flexibility measures, whereas girls do not.[101]

Pilot work suggests that increased hamstrings flexibility could be partially responsible for the decreased dynamic control of the knee in female athletes.[44,46] It appears that developmental differences in flexibility, especially hamstrings flexibility, might contribute to the postpubertal gender gap in knee injury rate; however, further research in this is needed. Lax hamstrings may lead to a delay in hamstrings muscle activation that results in an absence of co-contraction between the quadriceps and hamstrings muscle groups for a period of time early in foot strike.[30] Although hamstrings flexibility is not the only factor underlying the differences in ACL injury rates, it could be a potential contributor to increased ACL injury risk.

Increased Anterior Tibial Translation. The ACL limits the amount of tibial translation relative to the femur.[66] Uhorchak et al[113] reported that women with increased anterior-posterior laxity of the knee had a 2.7 times greater risk of ACL injury than did those without increased anterior-posterior laxity. Uhorchak et al[113] defined increased anterior-posterior laxity as a value of 1 SD or more above the mean. Rosene and Fogarty[89] reported that female athletes had higher mean anterior tibial translation than did their male counterparts at comparable progressive forces. They speculated that natural laxity in the female ligaments allows the tibia to shift anteriorly before the supporting muscles control the movement. The authors also speculated that the increased tibial translation is a sport-specific adaptation.[89] Tibial translation is related not only to ligamentous laxity but also to muscle activity. Tibial translation can be modulated by hamstrings and quadriceps activity.[104] Landing and pivoting sports involve a great deal of rapid deceleration and acceleration movements that push and pull the tibia anteriorly and place the ACL under stress.

Increased Foot Pronation and Navicular Drop. Women can also demonstrate a greater joint laxity in the foot. This increased ligamentous laxity is a possible cause of increased navicular drop in women.[62,110] Navicular drop could play a role in lower extremity alignment and tibial translation.[62,110] Trimble et al[110] reported that navicular drop was a significant postural predictor of tibial translation and suggested that there was a relationship between increased subtalar joint pronation and increased anterior translation of the tibia. Hence, increased navicular drop could move the tibia forward and increase strain on the ACL.[110] Loudon et al[62] concluded that there was an association between noncontact ACL injuries and subtalar joint overpronation. However, there are scant data on the navicular drop and its effects on knee motion and torque. More work is needed to determine the role of foot pronation in ACL injury risk.

Effects of Body Mass Index (BMI) and Age. Uhorchak et al[113] reported that height, weight, and BMI were significant indicators of ACL injury risk in female army recruits. They reported that women with a body weight or BMI greater than 1 SD above the mean had a 3.2 and 3.5 times greater risk of ACL injury than did those with lower body weight or BMI, respectively. Height and weight are potential predictors of knee injury risk in adolescent girls.[16] A longitudinal study of children 5 to 12 years of age in youth soccer demonstrated that there is no gender difference in knee injury risk in prepubescent athletes. However, age older than 11 years was a significant risk factor for knee injury in girls. For female players older than 8 years, BMI was also a significant risk factor for increased knee injury risk. These data yield an estimate of age 12 when knee injury rates begin to increase in female athletes, which consequently matches the timing of BMI increases in girls.[16] Therefore, chronological age and/or the increased BMI associated with pubertal development might play a role in the increased risk of ACL injuries in female athletes.

Biomechanical and Neuromuscular Changes During Pubertal Maturation. Contrary to the adolescent athlete, there is no evidence for a gender difference in ACL injury rates in prepubescent athletes.[1,16,68] Knee injuries do occur in the pediatric athlete, as 63% of sports-related injuries in children aged 6 to 12 years are joint sprains, and the majority of sprains occur at the knee.[36] Although ACL injuries increase with age in both male and female athletes, girls have higher rates immediately after the growth spurt.[112]

During puberty, the tibia and femur grow at a rapid rate in both boys and girls.[108] This growth of the 2 longest levers in the human body translates into greater torques on the knee.[42] Height increases lead to a higher center of mass, making muscular control of mass more challenging. Greater body mass translates into greater joint force that is more difficult to balance and dampen during high-velocity athletic movements. Power, strength, and coordination increase with age and maturational stage in males, which allows for increased dynamic lower extremity control needed to match the increased neuromuscular demands after puberty. Male and female neuromuscular patterns diverge during puberty,[42] as girls show decreased adaptation after puberty.[43] Thus, it appears that the growth and development associated with puberty are related to the neuromuscular, biomechanical, and perhaps hormonal factors that underlie the differences in ACL injury risk.[42]

Hormonal

Estrogen Effects on ACL Injury Incidence. Estrogen is purported to be an underlying cause of increased female ACL injury rates.[37,125] Moller-Nielson and Hammar[75] reported that women soccer players demonstrated a higher incidence of serious injury during the luteal phase of the menstrual cycle. Wojtys et al[118] observed a trend toward an increase in noncontact ACL injuries during the ovulatory phase of the menstrual cycle and a decrease in these injuries in the follicular phase of the cycle. Estrogen and relaxin concentrations peak during the ovulatory phase of the cycle.[92,93,115] However, Slauterbeck et al[102] reported the greatest number of ACL injuries occurred in the luteal phase of the menstrual cycle, just before menses (Figure 2). Myklebust et al[78] reported a greater number of ACL injuries in the follicular phase during menses. These findings are both equivocal and controversial.

One of the major problems in many of these articles is that there is no "ovulatory phase." The use of the term *ovulatory phase* is inappropriate. Ovulation is a single moment in time, not a phase, and if the menstrual cycle is divided into preovulatory and postovulatory phases, many of the published reports in the literature would likely be more consistent.

Estrogen Effects on ACL Strength. Decreased ligament strength due to cyclic changes in female hormones could be a possible contributor to female ACL injuries. Serum estrogen concentrations increase several fold during the cycle.[92,93,115] Both estrogen and relaxin are reported to affect the tensile properties of ligaments, and estrogen receptors are present in human ACL fibroblasts, whereas estradiol decreases procollagen synthesis in cultured fibroblasts from a female ACL.[15,58,92] Booth and Tipton[15] demonstrated that physiologic concentrations of estradiol significantly decrease ligament strength, and relaxin decreases soft tissue tension.[92] Strickland et al[107] reported no significant differences in maximum force, stiffness, energy to failure, or failure site

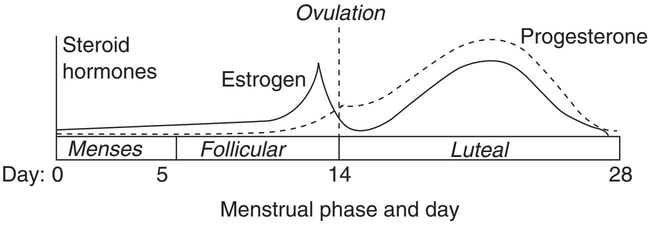

Figure 2. Changes in concentrations of estrogen and progesterone during the menstrual cycle. Estrogen concentration rises during the follicular phase, reaches a peak just before ovulation, and then drops sharply. It rises again and, along with progesterone, reaches a broad peak during the luteal phase. Estrogen and progesterone concentrations are both low during menses. Taken from National Athletic Trainers' Association.[102]

of ACLs from ovariectomized sheep compared with ovariectomized sheep with estrogen implants. Seneviratne et al[99] concluded that estrogen fluctuation across the menstrual cycle did not lead to clinically significant alterations in material properties of the sheep ACL in vivo. Several reports attribute ACL injury rate differences to increased passive joint laxity related to hormone cycling in women, whereas other reports refute this claim.[17,39,46,114,125] Wojtys et al[118] found an increase in laxity in the ovulatory phase of the menstrual cycle; Karageanes et al[50] found no difference. Heitz et al[40] reported that ACL laxity increased throughout the menstrual cycle. Thus, the contradictory data depicting the effects of hormones on the mechanical properties of the ACL could result from the fluctuating effects of estrogen and relaxin on ligament collagen and the lack of experimental control of this confounding variable.[94,118]

Effects of Estrogen on Neuromuscular Function and Control. Hormonal influences on neuromuscular control of the joints of the lower extremity could be an underlying mechanism for higher rates of ACL injury in female athletes. Estrogen both directly and indirectly affects the female neuromuscular system. Sarwar et al[94] reported quadriceps strength increases and a significant slowing of muscle relaxation during the ovulatory phase of the menstrual cycle. Serum estrogen concentrations fluctuate radically throughout the cycle, and estrogen has measurable effects on muscle function and tendon and ligament strength.[94] Estrogen also has effects on the central nervous system.[55] Lebrun[55] reported differences in isokinetic strength, anaerobic and aerobic capacity, and high-intensity endurance in female athletes during different phases of the menstrual cycle. Posthuma et al[88] demonstrated a decrease in motor skills in the premenstrual phase. These data indicate that estrogen has effects on neuromuscular function. Hormones are not the only factor underlying the differences in knee injury rate, but female hormones could be a significant contributor to the neuromuscular control of the knee joint.

Effects of Oral Contraceptives on Injury and Laxity. The data related to the use of oral contraceptives and their effects on mechanisms of ACL injury are not as equivocal as they are controversial. The question is whether oral contraceptives could potentially be prescribed to prevent ACL injuries. There are some data to suggest that such an intervention might be effective. Moller-Nielson and Hammar[75] reported that athletes taking oral contraceptives had a lower traumatic injury rate. The data of Arendt and Dick[2] and Wojtys et al[117] support the potential protective effects of oral contraceptives. Martineau et al[67] reported that oral contraceptive use decreased ligamentous laxity in female collegiate athletes. Estrogen peaks are known to have direct effects on muscle and may play a role in dynamic neuromuscular control of joints.[55,88,94] Significant slowing of muscle relaxation and increases in muscle fatigability have been demonstrated during the postovulatory phase of the menstrual cycle.[94] Oral contraceptives may block hormonal effects on dynamic (neuromuscular control) and passive (ACL laxity and integrity) knee stability by blunting the large fluxions, especially estrogen and estradiol peaks (Figure 2).

Neuromuscular

Antagonist-Agonist Relationships. Coactivation of the hamstrings and quadriceps muscles may protect the knee joint not only against excessive anterior drawer but also against knee abduction and dynamic lower extremity valgus. If the hamstrings are underrecruited or weak, quadriceps activation would have to be reduced to provide a net flexor moment required to perform the movement.[43,44] Deficits in strength and activation of the hamstrings directly limit the potential for muscular co-contraction to protect ligaments.[104] If hamstrings recruitment is high, the quadriceps can be highly activated, and a net internal knee flexor moment predominates. Similar mechanisms apply to muscular protection against torsional loading, in which gender differences have been identified.[119] Wojtys et al[119] demonstrated that maximal rotations of the tibia were greater in women than in men in both the relaxed and the active muscle state. Hence, women exhibited less muscular protection of the knee ligaments under internal rotation loading than did men.[119]

Another proposed theory related to neuromuscular mechanisms for increased ACL injury risk in female athletes is the relatively low knee flexor to extensor recruitment or hamstrings-to-quadriceps peak torque ratio in female compared with male athletes. Men demonstrate knee flexor moments that are 3-fold higher than those of women when decelerating from landing.[44] Women also demonstrate decreased hamstrings-to-quadriceps peak torque ratios and increased knee abduction (valgus) moments compared with male subjects.

Quadriceps contraction increases ACL strain in the first 30° to 45° of knee flexion, and isolated quadriceps contraction can produce forces beyond those required for ACL tensile failure.[29,59,74,79] Arms et al[3] demonstrated that ACL strain increased to 45° of flexion and decreased at knee flexion angles greater than 60°. Beynnon et al[10] reported that the ACL was strained by quadriceps contraction at 30° but not at 90° using in vivo techniques. They also reported that quadriceps contraction significantly increased at 15° and 30° but decreased at 60°.[13]

The ability to decelerate from a landing and control dynamic valgus and anterior tibial translation and rotation could be related to the decreased imbalance in the hamstrings-to-quadriceps strength and recruitment that was observed in the female athletes before neuromuscular training.[44] Co-contraction of the knee flexors is required to balance active contraction of the quadriceps to compress the joint and assist in the control of high knee abduction torques and anterior tibial translation.[104] Female athletes, with decreased ability to adequately balance muscular recruitment through positions of high joint loading, significantly increase their risk of subsequent ACL failure.[43] It is not likely that ACL injury is caused by either an isolated coronal or sagittal plane loading mechanism but rather through a combination of the 2 mechanisms.[34,47] Female athletes often demonstrate a predominately coronal plane strategy to control dynamic knee motion, which has been shown to be ineffective for adequate force dissipation during landing tasks.[17,21]

Solomonow et al[104] studied the synergistic action of the ACL and the thigh muscles in maintaining joint stability. They observed that direct stress on the ACL had a moderate inhibitory effect on the quadriceps but simultaneously excited the hamstrings. Similar responses were also obtained in patients with ACL damage during loaded knee extension with tibial subluxation, indicating that an alternative reflex arc unrelated to ACL receptors was available to maintain joint integrity. The hamstrings muscles clearly demonstrate their role as joint stabilizers in the patient who has a deficient ACL. Electromyographic studies have demonstrated that females have significant gender-related neuromuscular imbalances in quadriceps and hamstrings activation patterns.[98,116] During flexion exercises, female athletes demonstrate increased activation of their quadriceps relative to their hamstrings and increased anterior tibial loads during dynamic exercises.[65,98] Disproportional recruitment of the quadriceps musculature may lead to anterior shear force in female athletes. Thus, the available literature demonstrates several relationships between altered hamstring activation strategies and suggests its potential to be related to ACL injury.

Increased Anterior Shear, Decreased Co-contraction and Compression. Muscle strength and coordination have a direct effect on the mechanical loading of the ACL during sport movements.[77] The quadriceps, through the anterior pull of the patellar tendon on the tibia, contributes to ACL loading when knee flexion is less than 30° to 45°.[66] Hamstrings contraction compresses the joint, which is owing in part to the medial tibial plateau being slightly concave, and this factor could protect the ACL against anterior drawer force.[48] Such a protective effect of joint compression is reported in vivo for sagittal plane exercises.[29] Joint compression through muscular co-contraction allows more of the valgus load to be carried by articular contact forces, protecting the ligaments. Markolf et al[66] showed that muscular contraction can decrease both the valgus and varus laxity of the knee 3-fold.

Altered Magnitude and Timing of Muscle Activation. Electromyographic studies demonstrate gender-related differences in the timing of muscle activation during athletic maneuvers.[8,9,21,77,90,120,124] Huston and Wojtys[46] reported that female athletes have a slower response of hamstring activation to anterior stress on the ACL. Cowling and Steele[21] reported contradictory gender differences in hamstrings muscle activation. They reported that female hamstrings muscles were activated earlier than were male hamstrings muscles before landing. However, they speculated that the male pattern led to greater muscle synchrony that better controlled joint loading (peak anterior shear force) during landing. Besier et al[8] examined a sidestep cut at 2 different angles under both preplanned and unanticipated conditions and found increased varus-valgus and internal-external knee moments during unanticipated movements. They suggested that the increased coronal plane torques increased the potential for ACL injuries during unanticipated sport movements.[7] Lower extremity muscle activation during cutting is significantly different between preplanned and unanticipated conditions.[9] The unanticipated sidestep condition was reported to increase muscle activation in males 10% to 25%, with the greatest increase before initial contact.[9] Zazulak et al[124] reported greater peak rectus femoris activity in female athletes during the precontact phase of landing. Increased activation of the rectus femoris in female athletes could be an important neuromuscular contributor to increased ACL strain in women. Increased quadriceps activity combined with low hamstring activation contribute to lowered energy absorption in landing and increased ground reaction forces associated with ACL injury.

Preactivation of Protective Muscle Groups. Although ACL injuries occur too quickly for reflexive muscular activation, athletes can adopt or “preprogram” safer movement patterns that reduce injury risk during landing or pivoting or unexpected loads or perturbations during sports movements.[66] The lower extremity musculature is significantly (40%-80%) activated at the time that the foot touches the ground.[7,8] The muscular activation strategies of decreased medial quadriceps and hamstrings activation demonstrated by the female athletes limit the effectiveness of the active muscular control system to work synergistically with the passive joint restraints to create dynamic knee stability.[77,90] Muscle strength and coordination have a direct effect on the mechanical loading of the ACL during sport movements.[72,87] Preactivation of the quadriceps could be related to their increased valgus alignment at initial contact when performing cutting and landing maneuvers.[31,33,42]

Decreased Proprioception. The ACL not only holds the joint intact but is richly innervated and possesses specific mechanoreceptors.[51,95,96] The ACL functions as a sensor of torque and elongation of the ACL, which may indicate an anterior translation of the tibia on the femur. The ability of the ACL to sense the torque and elongation suggests that it is also vulnerable to these torques and translations. Nichols[82] and Chmielewski et al[19] have demonstrated that the agonist musculature fires in response to perturbations that put torque on a joint and that these firing patterns can be altered with neuromuscular training. The stretch reflex responds to stretch on the ACL by hamstrings activation.[104] Uninjured female subjects possess lower single-leg sway measures than do control males. However, after an ACL rupture, women have increased sway, indicating either a predisposition in high-risk females or greater trauma to the proprioceptive system of women after a tear.[39] Hence, proprioception deficits may play a role in ACL injury mechanism.

Imbalanced Medial-Lateral Muscle Firing Patterns. Rozzi et al[90] reported that female athletes demonstrate a disproportionate (4 times greater) firing of their lateral hamstrings compared with male athletes during the deceleration of a jump landing. Myer et al[77] reported a decreased ratio of medial quadriceps to lateral quadriceps recruitment. The decreased ratio of the medial quadriceps musculature recruitment combined with unbalanced medial hamstrings recruitment may be related to decreased control of coronal plane forces at the knee.[52,65,90] Coronal plane control of dynamic knee valgus is influenced by knee joint compression, especially medial condylar contact pressure. Decreased joint compression limits passive resistance to dynamic valgus and anterior tibial translation, predisposing the female knee to medial femoral condylar lift-off from the tibial plateau and increased loads on the ACL when decelerating a landing or cutting maneuver.[31,52,59]

Increased firing of the quadriceps musculature increases anterior shear force that directly loads the ACL.[65,98] In addition, unbalanced or low ratio of medial-to-lateral quadriceps recruitment observed in female athletes, combined with increased lateral hamstring firing, compresses the lateral joint, distracts the medial joint, and increases anterior shear force, which directly loads the ACL.[65,90,98] This neuromuscular strategy of unmatched lateral quadriceps firing, as evidenced by a decreased medial-to-lateral ratio, by the female athletes could be related to the increased propensity of women to demonstrate increased abduction motion and moments at the knee.[31,42,44] An unbalanced or low ratio of medial-to-lateral quadriceps recruitment combined with increased lateral hamstring firing would compress the lateral joint, open the medial joint and increase anterior shear force, which could potentially increase the risk of ACL injury.[90,98]

Increased Fatigue. There are relatively little published data to support a fatigue theory of ACL rupture, although sports medicine professionals often cite it as a potential mechanism. Nyland et al[84] reported that fatigue after eccentric quadriceps femoris work produced earlier gastrocnemius and delayed quadriceps femoris activation during crossover cutting in female athletes. They reported that fatigue from eccentric quadriceps femoris work produced delayed vastus medialis, rectus femoris, and vastus lateralis activation onsets compared with controls, but these parameters did not differ with hamstrings fatigue. Quadriceps femoris fatigue from eccentric work produced earlier gastrocnemius activation onsets than did controls, but gastrocnemius activation was not affected by hamstrings fatigue.[84]

Wojtys et al[119] studied the effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. The recruitment order of the lower extremity muscles in response to anterior tibial translation did not change with fatigue, but an increase in anterior tibial translation was observed with fatigue after a forward displacement of the calf by a motor-driven, dynamic stress-testing device. The increases in displacement after fatigue correlated with a delay in intermediate- and voluntary-level EMG activity. These authors concluded that muscle fatigue altered the neuromuscular response to anterior tibial translation. However, they did not demonstrate that fatigue affected the dynamic stability of the knee. The findings of these studies did not delineate the effects of fatigue; however, future research in this area could provide clues to common mechanisms of ACL injury in the female athlete.

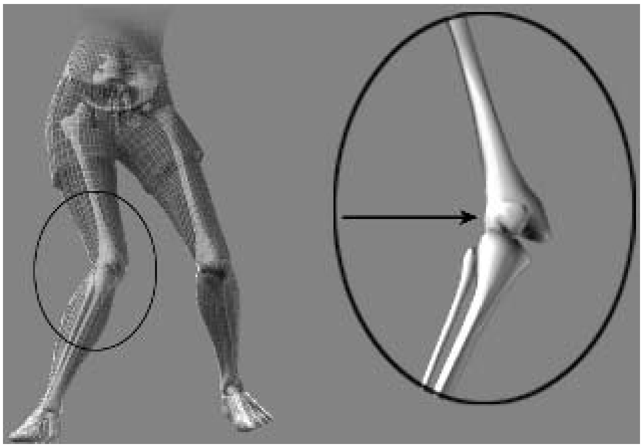

Figure 3. Example of dynamic lower extremity valgus, a combination of motions and rotations at all 3 lower extremity joints, potentially including hip adduction and internal rotation, knee abduction, tibial external rotation and anterior translation, and ankle eversion.

Biomechanical

Video Analyses of ACL Injury Mechanisms. Boden et al[14] outlined the body positioning that was related to most ACL injuries in a retrospective analysis. Video analysis of ACL injury during competitive sports play indicates a common body position associated with noncontact ACL injury in which the tibia is externally rotated, the knee is close to full extension, the foot is planted, and a deceleration occurs followed by valgus collapse (Figure 3).[14] Teitz[109] reported very similar positioning in the majority of ACL injuries she examined through video tape analysis. Male and female athletes become exposed to this general body alignment during competitive play. However, with sufficient neuromuscular control, knee stability can be maintained during competitive play without ACL injury. Teitz also pointed out that ACL injury occurred most often when the center of mass of the body is behind and away from the base of support (area of foot-to-ground contact).[109] Olsen et al[85] reported that dynamic valgus was the most common mechanism in handball.

Sagittal Plane Mechanism: Anterior Shear

Knee. The reported effects of gender on knee flexion angle vary widely. For example, during a sidestep maneuver, female athletes were reported to have less knee flexion during stance phase than did male athletes.[64] However, McLean et al[73] found no gender differences in athletes performing a similar maneuver. Ford et al[33] also found no difference in knee flexion during cutting and reacting to the unanticipated visual cue. Huston et al[45] showed significantly less knee flexion at initial contact during a drop landing from a 60-cm height but not from a 20-cm height. However, Fagenbaum and Darling[28] found that female athletes landed with significantly greater knee flexion angles compared with male athletes. Hence, there is no consensus as to whether female athletes land and cut with greater knee flexion than do male athletes. The balance of the evidence indicates that women maneuver with knee flexion angles near or equal to those of men.

Hewett et al[43] reported similar knee flexion angles at impact between female athletes who subsequently sustained ACL injury and uninjured athletes. Peak knee flexion moment values were similarly observed to be equivalent between groups. In addition, knee flexion angle at landing was not predictive of ACL injury risk. However, maximum knee flexion angles were 10° less in ACL-injured athletes than in uninjured athletes. McNair et al[74] reported that ACL injury occurred between 20° of knee flexion and full extension. Using video analyses, Olsen et al[85] and Boden et al[14] also reported that ACL injury occurred with the knee close to extension (between 0° and 30° of flexion). McLean et al[71] used a dynamic musculoskeletal model to demonstrate that peak anterior drawer force never exceeded loads that would be required for ACL rupture. On the contrary, valgus loads reached values that were high enough to rupture the ligament and occurred more frequently in women than in men. These authors concluded that sagittal plane knee joint forces could not rupture the ACL during cutting. Similarly, Pflum et al[87] used simulation modeling to predict ACL force during landing. The patellar tendon and tibiofemoral force both applied anterior shear forces to the shank throughout landing. However, these forces were lessened by a posterior shear force that limited the maximum force transmitted to the ACL. The authors concluded that quadriceps force was insufficient to rupture the ACL and suggested, like McLean et al, that valgus loading could generate high enough forces to rupture the ligament.

Hip. Hewett et al[43] reported differences in sagittal plane hip torques between female athletes who subsequently sustained ACL injury and uninjured athletes. Peak external hip flexion moment was greater in the group that sustained ACL injury compared with the uninjured athletes.[43] Zazulak et al[124] reported decreased gluteus maximus activity in female athletes compared with male athletes during single-legged landings. Devita and Skelly[25] evaluated ground reaction forces in soft and stiff landings (< 90° and > 90° of knee flexion, respectively). During a soft landing, lower extremity muscles were found to absorb 19% more of the body's kinetic energy, with the hip extensor eccentric contraction responsible for 22% of the total kinetic energy.[21] Decker et al[22] reported that female athletes experience high ground reaction forces at the lower extremity during landing because of decreased use of the hip musculature to absorb these forces. In contrast to male athletes, who use the hip musculature to a greater extent to absorb energy, female athletes may adopt landing strategies in which more energy is absorbed at the knee and ankle.[22] Therefore, hip control could be involved in the ACL injury mechanism; however, more study of neuromuscular control of the hip is necessary before conclusions can be drawn.

Ankle. Kinematic differences at the ankle may also contribute to gender differences in ACL injury rates.[38] Variations in ankle joint angles have been shown to influence joint forces, moments, and muscular activation patterns.[32,38] Sagittal plane ankle position in female athletes with ACL injury has not been well characterized and requires further study.

Coronal Plane Mechanisms for Increased ACL Rupture

Knee. The gender-based disparity observed in ACL injury rates is strongly influenced by differences in the coronal plane joint motions and torques. The link between dynamic valgus knee loading and resultant increases in ACL strain is demonstrated through cadaveric, in vivo, and computer modeling experiments.[35,49,61,65] Physiologic dynamic valgus torques on the knee can significantly increase anterior tibial translation and load on the ACL several-fold.[35] The terms *valgus* or *dynamic valgus* or *dynamic lower extremity valgus* are used interchangeably throughout this review and are not limited to the knee but are a combination of motions and rotations at all 3 lower extremity joints, potentially including hip adduction and internal rotation, knee abduction, tibial external rotation and anterior translation, and ankle eversion.

A prospective, combined biomechanical-epidemiologic study showed that knee abduction moments (valgus torques) and angles were significant predictors of future ACL injury risk.[43] Knee abduction moments, which directly contribute to lower extremity dynamic valgus and knee joint load, predicted ACL injury risk with 73% sensitivity and 78% specificity.[43] Knee abduction was more than 8° greater in the ACL-injured group than in the uninjured groups. Knee abduction angle correlated to peak vertical ground reaction force in ACL-injured athletes. Knee flexion angle was not a strong predictor of future ACL injury.[43] It is therefore likely that the increases observed in valgus measures in the injured cohort were a significant component of the mechanism that led to ACL rupture.

Ford et al,[33] using highly accurate and reproducible 3D motion analysis techniques, reported that female athletes had a greater knee abduction angle when preparing to execute a cutting maneuver compared with male athletes. However, there was no difference in knee flexion angle between genders. Gender differences in knee abduction angle are indicative of altered dynamic neuromuscular control of the lower extremity in the coronal plane. These kinematic differences likely reflect gender differences in contraction patterns of the adductors and abductors of the knee and hip.[12,43,65]

Hip. Hip angles during landing can be important determinants of impact force at the knee.[20,45,64] Women have gender-related neuromuscular imbalances in muscle contraction patterns that include increased rectus femoris firing and decreased gluteal muscle firing.[98,116] Repeated performance of the high-risk maneuvers with insufficient hip control of motion in the transverse plane may lead to the valgus collapse and ACL rupture.[14,42,109] Ford et al[31] reported dominant versus nondominant differences in hip stabilization during landing. Women landed with greater external hip adduction moments and decreased hip flexion angles on the dominant side. Side-to-side imbalances in neuromuscular strength, flexibility, and coordination can be important predictors of increased injury risk.[5,43,53] Increased side-to-side differences and decreased activation of the hip musculature could increase valgus knee positioning and risk noncontact ACL injuries.

The hip abductor muscles may play an important role in controlling excessive valgus motion and torque in female athletes.[77] Increased ability to decelerate from landing and control dynamic valgus might be related to hip muscle strength and recruitment. Female athletes have greater external hip adduction moments during landing. The increased external hip adduction moment could indicate that women have difficulty controlling the hip, especially resisting adduction, during dynamic sports movement. Dynamic coupling between segments of the kinetic chain combined with asymmetry of hip ad/adductor muscle activation could lead to the dynamic valgus position of the knee exhibited in female landing patterns.[31,44]

Ankle. Increased ankle eversion is a potential factor related to the gender differences found in ACL injury rates. Ford et al[33] demonstrated that female athletes had greater maximum ankle eversion than did male athletes during the stance phase of cutting. Increased valgus knee stress, anterior tibial translation and increased loading on the ACL result from excessive eversion.[62,83] This outcome is owing in part to a coupling of foot pronation and internal tibial rotation.[6,76,83,110] A near-linear correlation exists between foot eversion and tibial internal rotation.[6] Valgus positioning can be increased when combined with ankle eversion and tibial rotation later in the stance phase.[33] However, the contributions of the ankle to coronal plane mechanisms of ACL injury are relatively unclear.

Transverse Plane Mechanism of ACL Injury

Knee. Internal and external rotation motions and torques likely contribute to the ACL injury mechanism.[72] Besier et al[8] examined a sidestep cut at 2 different angles under both preplanned and unanticipated conditions. They reported increased internal-external knee moments during unanticipated sports movement and suggested that there is increased potential for noncontact knee injuries during unanticipated movements. Lower extremity muscle activation during cutting is different between preplanned and unanticipated conditions.[9] An unanticipated sidestep condition was reported to increase muscle activation 10% to 25%.[9]

Hip. The hip is a potentially important controller of dynamic joint stability in female athletes.[56,69,78] Decreased activation of proximal stabilizing muscles can alter load-bearing capacity and result in higher loads per body weight at the knee in the transverse, sagittal, and coronal planes. Lephart et al[57] reported that female collegiate athletes demonstrated greater hip internal rotation maximum angular displacement than did male athletes during landing. The gluteus maximus is an external rotator as well as extensor and abductor of the hip.[24] It may play an important role in controlling the excessive hip rotation demonstrated in female athletes during dynamic movement.[70] Zazulak et al[124] reported significantly lower gluteal EMG activity in female athletes compared with male athletes during landing. These observed increases in hip internal rotation and decreases in hip muscle activation could increase the loads that are associated with increased strains on the ACL.[12,65]

Ankle. Subtalar joint pronation measured by navicular drop was reported to be greater in ACL-injured patients compared with controls.[62] Other studies refute these findings.[110] The contributions of the ankle to transverse plane mechanisms of ACL injury remain unclear and are a wide open area for future research.

Unanticipated Situations and Movements. Rapid, unanticipated changes of direction are often cited as a common mechanism for noncontact ACL ruptures.[14,74] In team handball, for example, approximately 80% of ACL injuries occurred during a plant-and-cut movement or while landing from a jump.[79] High-risk movements (ie, cutting, rotating, and landing) occur as often as 70% of basketball play.[106] These movements are typically not planned or anticipated, so the athlete must react during the game to a ball or a defensive player. Ford et al[33] reported gender differences in lower extremity valgus during unanticipated cutting. Besier et al[8] found increased varus-valgus and internal-external knee moments during unanticipated movements and suggested that there is increased potential for noncontact knee injuries during unanticipated sport movements. Olsen et al,[85] in a study of mechanisms of injury in team handball, determined that ACL injuries occurred most often by a plant-and-cut mechanism and by single-leg landing from a jump shot (Figure 4), which was the second most common mechanism. Other attacking injuries occurred when the players were running forward or decelerating without change of direction that occurred when landing on one foot.[85] Postural adjustments and reflex responses can be altered owing to the anticipation of a sports movement.[7] The limited time to make postural adjustments during unanticipated situations in high-risk sports may contribute to ACL injury mechanisms.[8]

Prior Injury

Prior injury is one of the single best predictors of future injury risk.[43,111] This concept applies to ACL injuries as well as injuries in general.[43] For the ACL, however, injuries to the contralateral knee are even more common than reinjuries. Shelbourne et al[100] reported contralateral tears of 1 in 26 knees and retears of 1 in 38 knees. In a small retrospective cohort of videographed ACL injuries, Boden et al[14] reported that 10% went on to bilateral injury.

Dunn et al[26] studied the effect of ACL reconstruction on the risk of ACL reinjury in a large population of young active patients (>6000). The rate of reoperation was significantly lower in the ACL reconstruction group compared with those treated nonoperatively. Younger age was the strongest predictor of failure of nonoperative management leading to late ACL reconstruction. However, there is a lack of objective data demonstrating that ACL injury is prevented by reconstruction. Prior knee or lower extremity injury can be a good predictor of future ACL risk.

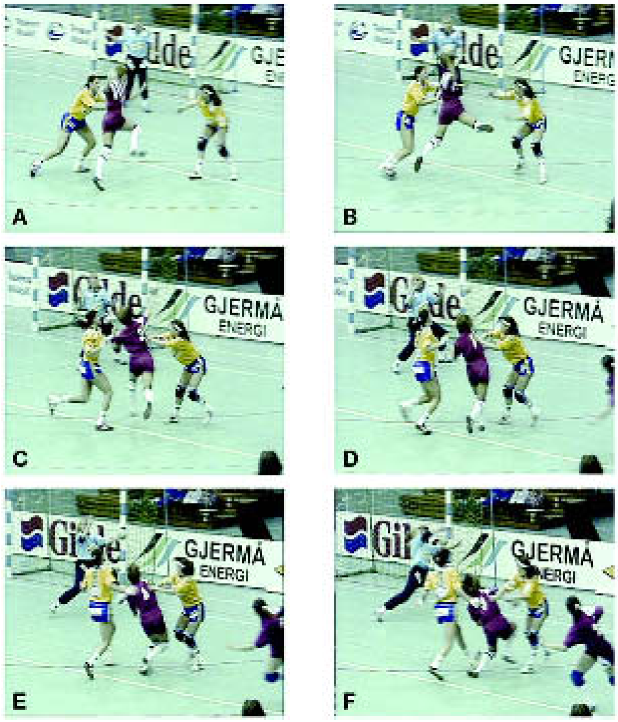

Figure 4. Injury mechanisms for ACL injuries in team handball: a systematic video analysis. From Olsen et al.[85]

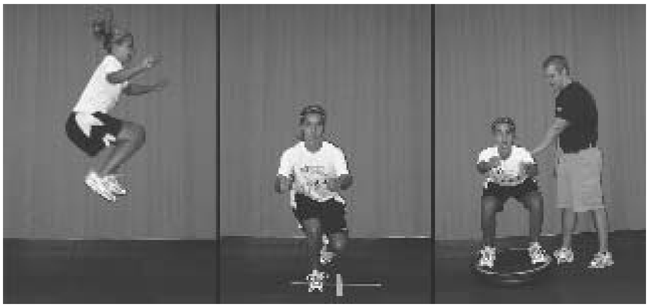

Figure 5. Example of 3 components of dynamic neuromuscular training: plyometrics, single-limb balance, and perturbations.

CONCLUSION

Increased ACL injury incidence in female athletes is likely a multifactorial musculoskeletal disorder. Potential factors that have not been discussed may play a role (eg, genetics). In addition, injury data from many fields demonstrate that numerous physical and psychological parameters affect injury rates. Although there likely are multiple factors underlying the differences in ACL injury rates in male and female athletes, neuromuscular control may be important to injury risk and the most modifiable factor. Although the focus should remain in areas that are modifiable, in which effective interventions can be developed, investigations should continue into the relative contribution of less modifiable factors. This research is especially important in the pubescent athlete, for whom significant developmental changes occur both anatomically and hormonally. The musculoskeletal changes that can both alter passive joint laxity and decrease dynamic joint stability in high-risk female athletes and potentially lead to higher injury rates in this population could be modified if interventions were instituted at the appropriate stages of development.

Neuromuscular training in female athletes has been shown to increase active knee stabilization in the laboratory and decrease the incidence of ACL injury, on the court or field, in athletic female populations.[41,44,78] Neuromuscular training facilitates neuromuscular adaptations that teach athletes to use joint stabilization patterns that employ safer muscular prestance and midstance activation patterns (Figure 5). This training allows female athletes to adopt muscular recruitment strategies that decrease joint motion and protect the ACL from the high-impulse loading during performance.[60,77,105] However, a more clear identification of the modifiable mechanisms would increase the potential for both screening for high-risk athletes and targeting interventions to address the specific mechanisms that increase ACL injury risk in female athletes.

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