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The female ACL: why is it more prone to injury?

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Female athletes tear their anterior cruciate ligaments (ACL) at an alarmingly higher rate in certain sports that involve rapid stopping, cutting, and changing direction, including basketball, team handball, and soccer. The participation in sports by girls has increased dramatically since the National Federation of State High School Associations began recording the numbers [1]. For the 1999–2000 season, total participation by high school athletes for males was 3,861,749, females 2,675,874, and coed 19,289. For sports in which both males and females compete, the basketball numbers for males was 541,130 compared to females 451,600, track—males 480,791, females 405,305, and soccer—males 330,044 and females 270,273. The growth and ratios of male to female in 1970 was 12:5:1, 1985–1986—19:1, and 1999–2000—1.4:1. The rapidly increasing numbers of females participating impacts the number of injuries. However, the rates of ACL injuries in comparable sports of basketball and soccer have ramined alarmingly high with change in male-to-female ratios over the last 10 years [2]. At the NCAA level, injury surveillance statistics, which are based on exposure rates, document the discrepancy in ACL injuries in females compared to males. The incidence of female to male is 3.5 times greater in basketball and 2.8 times greater in soccer [3,4] (Figs. 1 and 2) This article will discuss the most significant factors for tears of the anterior cruciate ligament in the female athlete.

The typical mechanism of injury is a rapid but awkward stop and anticipation of lateral movements [5–7]. Analysis by videotapes has allowed the description of the position of no return (Fig. 3). In this basketball athlete, she is noted to be in a relatively upright position with less flexion of the hip and knee, relatively straight back, momentum forward, and then excessive valgus at the knee. The ACL tears in 70 milliseconds [8]. An awkward landing occurs often when she is on offense in basketball trying to shoot, land, rebound, and keep from going out of bounds. The exact point of ACL failure is just prior to the gross valgus. If one concentrates on the hip with an abducted and internally rotated femur, and in little hip flexion, forward proximal position dictates the knee and leg and foot position. The knee injury is the result or "victim"of more proximal hip position and muscle activity. Proximal instability results in lower extremity injury. The position of no return concept has been developed by analysis of many videos showing noncontact ACL injury (Fig. 4). A safe landing position is more knee flexed, hip flexed. The joint position will also determine how quickly and effectively muscles can fire to prevent injury. In a more flexed position, the hamstrings are more effective at preventing anterior tibial translation. Thinking of body alignment and how this influences muscle activity has been developed based on looking at injury patterns, but this can also be applied to prevention strategies. Staying in the safe landing position, with a more flexed hip, knee, and normal lumbar lordosis allows better postural awareness and more coordinated landing. The hip flexors, adductors, and iliopsoas increase the hip internal rotation and abduction. To remain upright, the landing typically is tibia external rotation, forefoot pronation. The firing of the quadriceps, foot dorsiflexors, and tibialis anterior allows the athlete to remain upright.

Gender differences are obvious when observing position of the pelvis and hip in individuals doing a simple step-down maneuver from a height. These noninjured individuals demonstrate the typical male strategy when asked to do a mini-squat of hip directly

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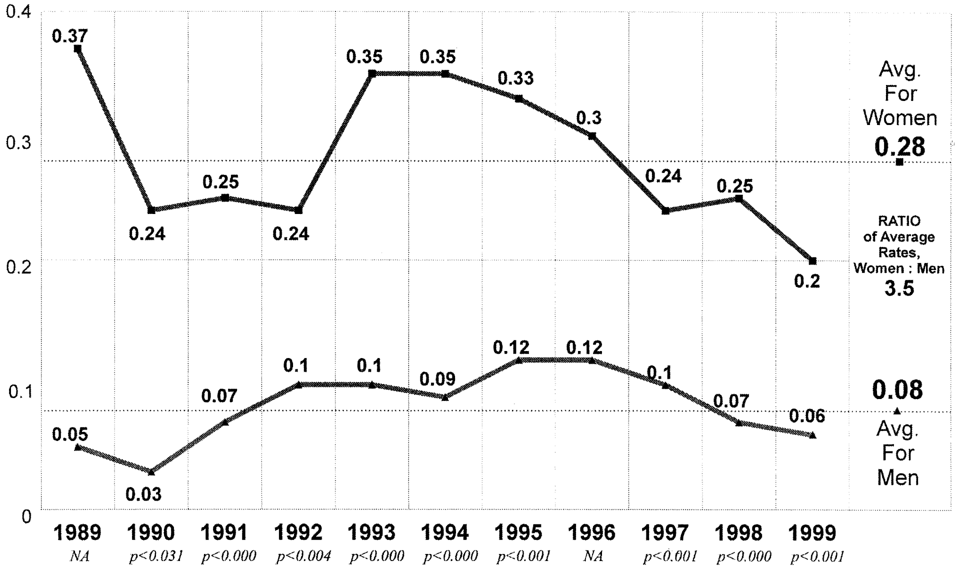

Fig. 1. Yearly NCAA rates of injury to the ACL, comparing women and men: basketball, 1989–1990 season through 1999–2000 season. Injury rates represent injuries/1000 athlete exposures. (Copyright 2002, ML Ireland. Data from NCAA Injury Surveillance System; *adapted from* Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. J Athletic Training 1999;34(2):86–92.)

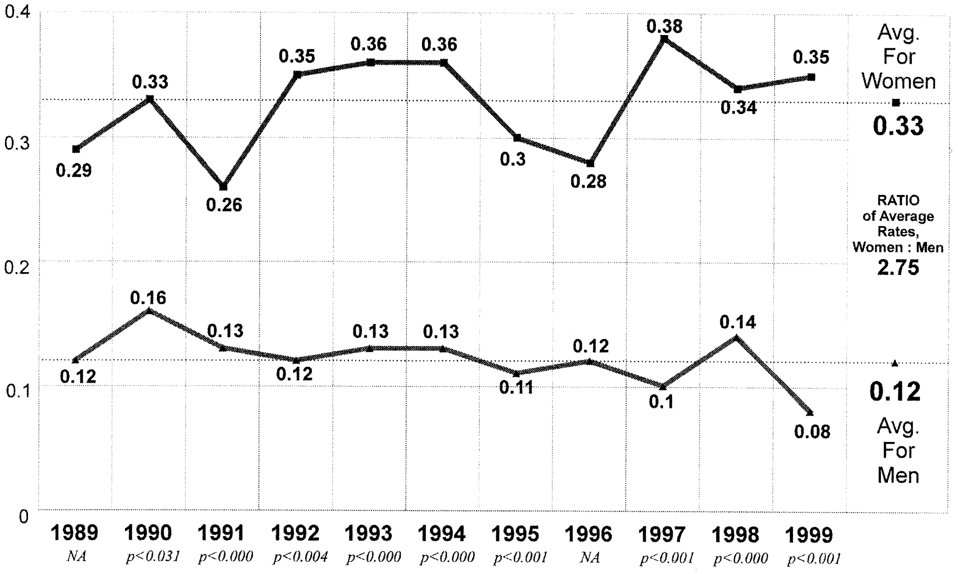

Fig. 2. Yearly NCAA rates of injury to the ACL, comparing women and men: soccer. (Copyright 2002, ML Ireland. Data from NCAA Injury Surveillance System; *adapted from* Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. J Athletic Training 1999;34(2):86–92.)

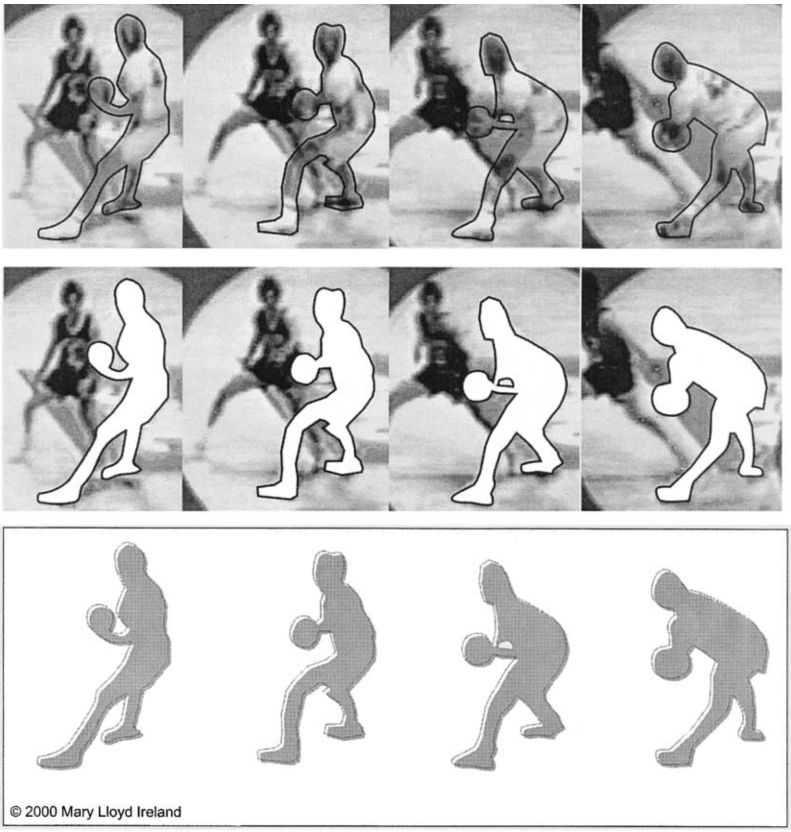

Fig. 3. Analysis by videotape—basketball athlete. Injury to the left knee as observed from the back and left side of the athlete. She has just rebounded and stops to change direction to avoid the defending player. She lands in an upright position with less knee and hip flexion, and forward-flexed lumbar spine. After the ACL fails, she falls forward and knee valgus rotation and flexion increase. She is unable to upright herself and regain pelvis control to avoid ACL injury. (Copyright 1999, ML Ireland.)

over knee over ankle. The female demonstrates the femur position in hip adduction internal rotation creating valgus at the knee and tibial external rotation and forefoot pronation (Fig. 5).

Seen from the lateral view, the male demonstrates a relative flat back and posterior rotated position, and the female demonstrates an anteriorly rotated position or increased lumbar lordosis in an anteriorly rotated pelvis position (Fig. 6). The proximal position determines position of the knee. The knee is the victim of the more proximal pelvis and hip position of hip adduction and internal rotation and anterior pelvic rotation.

The concept of hamstring dyssynchronization with inability of hamstring control proximally, leading to anterior tilt of the pelvis, has been popularized by Hruska and others [5–9]. The lordotic spine, anteriorly rotated pelvis creates trunk and pelvic dyssynchronism, resulting in the distal rotational abnormality of internal rotation and adduction of the femur and subsequent external rotation of the tibia and pronation of the foot (Fig. 7).

Contributing factors

Noncontact ACL injuries are multifactorial. It is helpful to think of these factors in different categories: intrinsic (not changeable), extrinsic (changeable), and combination (both) (Table 1). There are multiple factors involved. Intrinsic factors include alignment, hyperextension, physiologic rotatory laxity, ACL size, femoral notch size and shape, hormonal influences, inherited skills, and coordination. Extrinsic factors include strength, conditioning, shoes, and motivation. Combined factors (potentially changeable) include proprioception (position sense/balance), neuromuscular, order of firing, and acquired skills. Balance and order of neuromuscular

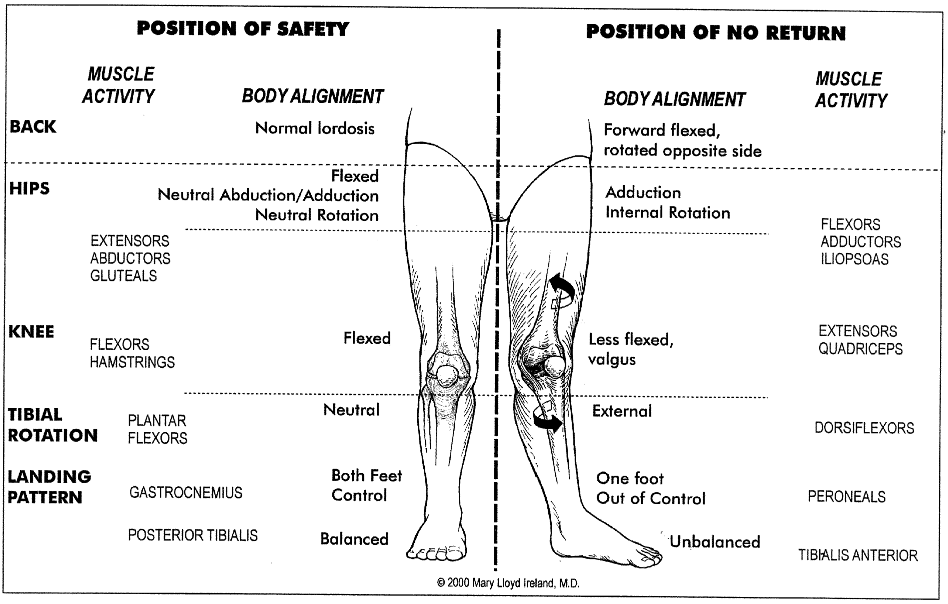

Fig. 4. The position-of-no-return mechanism for ACL injury and the safe position. (Copyright 2002, ML Ireland.)

activation patterns are very important. Dynamic movement patterns, not static anatomic measurements, are the most important factors contributing to ACL injury [10].

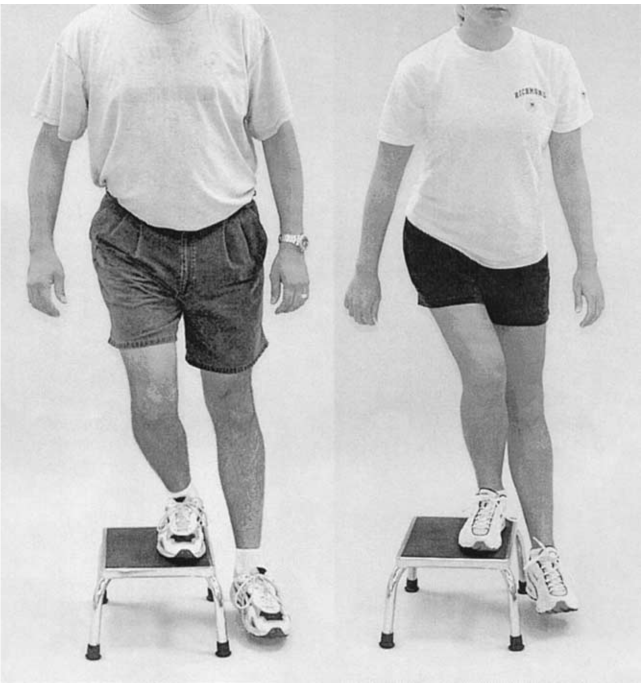

Fig. 5. When instructed to do a minisquat the male (left) demonstrates hip over knee over ankle alignment; the female (right) demonstrates femoral adduction and internal rotation and subsequent external rotation, valgus of the knee, and forefoot pronation.

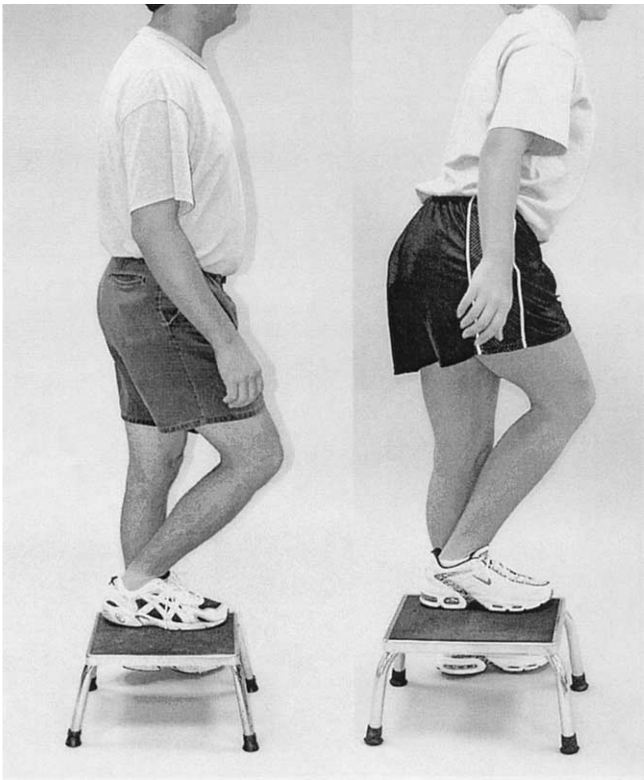

Fig. 6. Seen from the side view, the female (right) is seen to have an anteriorly rotated pelvis, forward head, and forward trunk position compared with the male (left), who has a straight upright posture with normal lumbar lordosis. The anterior pelvis position creates lower extremity rotational compensation patterns. (Copyright 2001, ML Ireland.)

The extrinsic or changeable factors are controlled by the player and coaches. She must be motivated to do an in-season or off-season strength and conditioning program. These programs are not required to be, nor should they be, exactly like the programs for the male athlete. Sports-specific movement patterns and strengthening of muscle groups at multiple joints are necessary. The floor surface and shoe surface interface are other extrinsic factors. A surface that allows the foot to skid is more forgiving than the Tartan basketball court.

Risk factors that are potentially changeable are proprioception or position sense balance for which training would include the wobble balance boards and landing strategies. Neuromuscular factors of the order of firing of the lower extremity from low back distally from the lumbopelvic level and distal segments must be evaluated. Assessment of the quality of movement is subjective, but high-risk players can be selected by observation of skilled medical personnel. The preinjury ACL takes many risks and lands in an awkward, sometimes more upright, out-of-control position.

Factors that are not changeable or intrinsic include alignment and ACL size (which is directly related to the size of the notch). Inherited factors of the way we move and land and level of coordination are also in the nature, not nurture, category. The female athlete is hypermobile, in that she often has hyperextension of her joints, particularly her knee. An associated but different feature is the physiologic internal rotatory instability, where she may have a mild pivot shift or glide. This excessive capsular laxity allows the tibia to begin to anteriorly sublux during a landing maneuver. The question remains: Is this laxity protective or does it cause excessive anterior subluxation that the hamstring strength and reaction time is unable to prevent the ACL from tearing in a noncontact mechanism?

Consensus statement

A consensus conference was held in Hunt Valley, Maryland, on June 10, 1999, sponsored by the

American Orthopaedic Society for Sports Medicine (AOSSM), National Athletic Trainers' Association (NATA), National Collegiate Athletic Association (NCAA), and Orthopedic Research and Education Foundation (OREF). The goal of the conference was to discuss anatomic, environmental, hormonal, and biomechanical risk factors for noncontact ACL injuries; specifically, what we know from the written information, areas for further research, and prevention strategies. From the written information and presentation of the 12 physicians and 9 basic researchers at this retreat, a prevention booklet was published [10,11]. The categories of risk factors were anatomic, environmental, hormonal, and biomechanical. Neuromuscular factors appear to be the most important reason for the higher rate of ACL injuries in females compared to males [11]. The at-risk situations for noncontact ACL injuries appear to be deceleration, cutting or changing directions, and landing. Prior to the injury, an awkward dynamic body movement and a perturbation event are usually observed. With this, quadriceps activation during eccentric contraction is a major factor in ACL injury during the at risk maneuver.

Environmental factors potentially contributing to ACL injuries are the shoe–surface interface and bracing. The shoe surface coefficient of friction may improve performance but also may increase the risk of injury to the ACL. Because it is modifiable, shoe–surface interaction merits further investigation. There is no evidence that knee braces prevent ACL injury.

Anatomic risk factors of the femoral notch and lower extremity alignment were discussed. Although there is much literature on the role of the femoral notch size in ACL injury, no consensus on the notch's role in ACL injury can be reached at this time. It is difficult to achieve valid and internally and externally reliable measurements. There is insufficient data on ACL size measured by direct notch or notch width index measurement to support that ligament size is related to risk of injury. The question remains: is a small ligament more apt to fail than a large ligament?

Table 1
Factors contributing to ACL injuries

Instrinsic	Extrinsic	Combined (potentially changeable)
Alignment	Strength	Proprioception Position sense/ balance
Hyperextension	Conditioning	
Physiologic rotatory laxity	Shoes	Neuromuscular Patterns
ACL size	Motivation	Order of firing
Notch size/shape		Acquired skills
Hormonal influences		
Inherited skills/coordination		

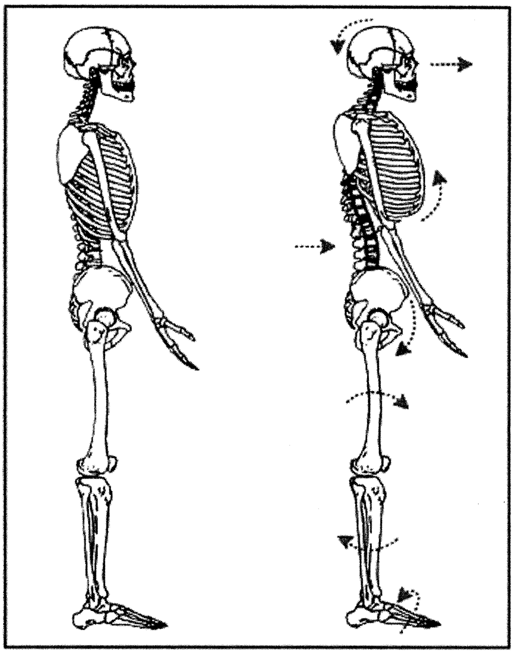

Fig. 7. The sequence of displacements from an anterior pelvic tilt includes forward pelvic rotation, femoral internal rotation, medial displacement of the femoral range of rotation, genu valgus, genu recurvatum, subtalar eversion, and forefoot or rear-foot pronation. (*From* Hruska R. Pelvic stability: influences lower-extremity kinematics. Biomechanics 1998;5:24, with permission.)

Hormonal influences have also been studied. There is no consensus in the scientific community that sex-specific hormones play a role in the increased incidence of ACL injury in female athletes. There is sufficient evidence to warrant continued investigation of hormonal influences on ACL injury. Currently, there are no recommendations for hormonal intervention or modification of participation in sports at anytime during the menstrual cycle. There is no justification for sex-specific hormonal manipulation to prevent ACL injuries.

Specific training programs that enhance body control may reduce ACL injury rates and may increase athletic performance in females. Training and conditioning programs for male and female athletes in the same sport may need to be different. Identifying sports-specific at-risk motions and positions and encouraging athletes to avoid these at-risk situations when possible seems promising. Further, strategies for activating protective neuromuscular responses when at-risk situations are encountered is also a possible prevention strategy.

There is a need to improve public and participant awareness for risk of ACL injury and the possibilities for prevention. We need to continue to define the specific neuromuscular, proprioceptive, and motor control factors associated with ACL injury. Although specific predictive and protective factors are determined, training and prevention programs should continue to be implemented, assessed, and improved. From this consensus conference a monograph of prevention strategies has been published [10].

Hormonal

Sex hormones have effects on numerous end organs, as evidenced by changes during menarche and menopause. Estrogen, progesterone, relaxin, and other sex hormones have cyclic effects. There is no consensus of the scientific community that sex hormones play a role in the increased incidence of ACL injury in female athletes [11]. One must understand the hormonal activities during the cycle and the hormonal effects during the cycle [12] (Fig. 8). The cycle number begins with menses. The follicular phase is day 1 to 9, ovulatory, day 10 to 14, and luteal, day 15 to 28. Estradiol peak occurs just prior to ovulation when there is a luteal hormone spike. Ovulation occurs over a shorter period of time than 4 days—24 to 36 hours. There are many reports in the literature regarding ACL injuries and relationship to phase of the cycle. The cycle time can be documented by history alone, hormonal levels measured in saliva, blood, urine.

ACL injuries have been reported to be higher in the ovulatory phase. In 1998, Wojtys et al [13] reported on a series of 28 women who were found to have more ACL injuries than expected during the ovulatory phase and fewer injuries during the follicular phase at a p-value of 0.03. However, reevaluation of these data led to the discovery that the results were not statistically significant but only showed a trend [14]. More recently, Wojtys et al have reported on 69 females with acute ACL injuries studied within 24 hours at four centers by menstrual cycle details and urinary hormonal levels. These results supported a significantly greater than expected percentage of ACL injuries during midcycle (ovulatory phase) and less than expected during the luteal or follicular phase [15]. Wojtys reported that oral contraceptives reduce the rate of ACL tear in the ovulatory phase. However, no recommendations are being made to modify practices, activity level, or place females on oral contraceptive pills in the face of these results [3,11]. In the follicular stage, ACL injuries have been reported to be less by Wojtys. Mykleburst [16] reported higher rates of ACL injury 1 week before menses and just after menses. Slauterbeck and Hardy also found higher ACL rates before and after menses [16,17].

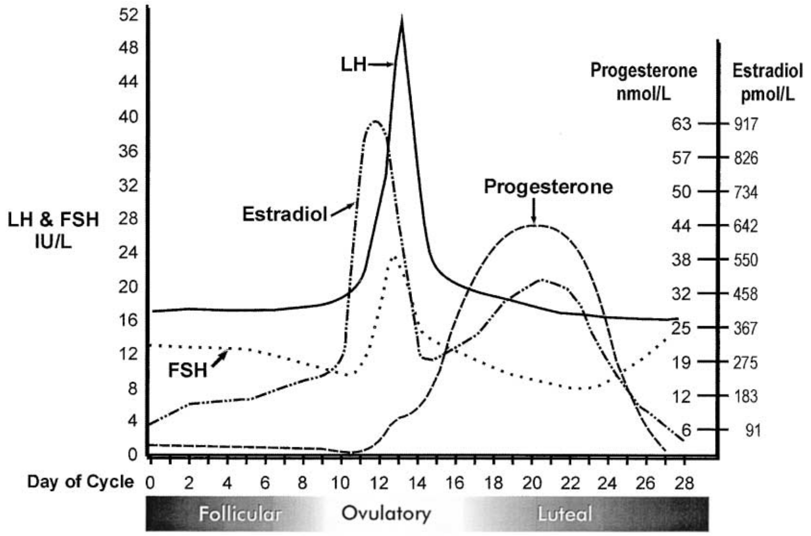

Fig. 8. Hormonal changes during the menstrual cycle (Adapted by Dr. J.D. Prior from: Speroff L, Van De Wiele FL. Regulation of the human menstrual cycle. Am J Obstet Gynecol 1971;109:234–47, with permission.)

Further studies must be done on hormonal effects on musculoskeletal injury as well as effects of oral birth control pills on injury patterns.

The effect of the hormone on the ligament and production of fibroblasts and collagen has been reported to be reduced when estrogen is high [18]. However, the cyclic and spike of estradiol's direct effect on the ACL is unknown. Certainly, there are effects on other collagen structures (capsule, muscle, tendons) psychologic effects of reaction times, ability to fire the muscles effectively, and aggression of play. In a study performed on 38 sheep, mechanical properties of the knee ligaments were assessed after hormonal treatment. The ACL and medial collateral ligament (MCL) were mechanically tested, and the effect of estrogen or estrogen receptor agonist were not demonstrated in these ewe new ligaments. Therefore, there is no demonstrable effect of estrogen directly on ligaments [19].

Anatomic differences

The lower extremity static alignment and measurements have not been predictive of ACL injuries [11,20]. Authors frequently state that the female has a wider pelvis than the male. However, females have a narrower pelvis.

Horton and Hall, in 50 males and 50 females, all asymptomatic, found that males had a greater hip width by 3 cm and longer femoral length by 5 cm [21]. The ratios of hip width to femoral length were about equal—0.73 in males and 0.77 in females. Ratios appear to be a more important measurement than absolute width. In another study comparing gender in normal, noninjured knees, 31 males and 35 females were studied. In measurements of Q angle, anterior superior iliac spine to opposite spine bitrochanteric breadths, and femoral widths, females were found to have a slightly larger Q angle but less mean by trochanteric breadth compared to males, with measurements not being statistically significant. The femoral lengths were significant, with the mean femoral length in males 1.5 cm greater than in females.

Livingston and Gahagan analyzed uninjured young adult males (n = 31) and females (n = 35) for measurements of pelvic widths and femoral lengths and Q angles in the weight-bearing position. Females had a smaller pelvic width measuring from anterior superior iliac spine (ASIS)-to-ASIS and greater trochanter to greater trochanter compared to males, but the differences were not statistically significant. However, the femoral length differences were significant, with new femur length 1.5 cm greater for males. Q angles were slightly greater in females than males, 9.8 compared to 10.2. The relationship between pelvic or hip width Q angle and increased rate of knee injuries is a common assumption, but has not been proven in the literature. Ratios of pelvic width to femoral length may provide more injury predictive information than absolute widths or lengths [22]. During growth, the lanky, longer legged individual has a greater ratio of lower-to-upper body segments. This individual may have less ability to safely control knee movements and tear the ACL or develop patellofemoral disorders. However, comparing gender, the ratio of upper to lower extremity length is only slightly, but not significantly greater, in males than females in all ages [23]. Children today have greater height and weight, and undergo puberty earlier [24].

Pelvic and femoral development

Clinical anatomists provide the clinician with unique perspectives and measurements. The characteristics of the pelvis and femur are used to determine race. Lateral radiographs of the femur were performed, and measurements of the notch and shelf angle, the angle between Blumensaat's line and the posterior shaft of the femur, were made [25]. The White race had a significantly higher shelf angle (146.2 mean) than Blacks (137.8 mean) in a sample of 423 femora. The anterior curvature of the femur has also been reported to be less in Blacks than Whites [26]. This unique perspective of identifying the gender and race from skeletal remains offers us a different perspective.

Genetics, culture, and environment determine pelvic shape [27]

There are numerous measurements of the pelvis reported by clinical anatomists [18,28,29]. Variations in pelvic measurement are more often shape, sites of muscle origin, femoral and acetabular orientation, and not pelvic width. The pelvis has less variability in morphology in females [29]. In the Lapp population, characteristics of normal and dislocated hips were evaluated with measurements of antetorsion, neck–shaft angle, acetabular depth, acetabular depth and inclination, platymery, and pilaster [30]. The index of platymery as the sagittal to the transverse diameter of the proximal femoral diaphysis is usually more pronounced in women than men. This ratio and increased platymery number has been shown to occur with lateral enlargement of the insertion of the gluteus maximus and with a larger degree of antetorsion. In this Lapp population, females had a greater antetorsion angle by 2.3 degrees. Females had a significantly greater antetorsion angle, greater than 20 degrees by 34.5% in females compared to 22.4% in males.

Femoral anteversion or antetorsion can be measured clinically by prone hip rotation as described by Staheli [31], but it is difficult to measure radiographically. Torsion is the deformation of the body, such as a rod, by twisting one end held fast and the other end is turned around on its length on the axis [32]. A plus angle indicates the femoral neck axis is pointing forward or anterior to the frontal plane, and is referred to as anteversion, antetorsion, or anterior twist. As described in April 1953, a posteroanterior (PA) pelvis and hip lateral radiograph of the hip using a radiopaque reference bar can give a true angle of torsion [33].

Staheli et al measured 1000 normal lower extremities in children and adults with five clinical measurement: foot progression angle, medial and lateral rotation of the hip, thigh–foot angle, and angle of the transmalleolar axis. Medial hip rotation was greater in female than in male subjects by a mean difference of 7 degrees, and declined from middle childhood onward. There were no differences in the lateral rotation of the hip comparing sexes [34]. CT scans can more accurately measure the relationship of the femoral condyle, which remains fixed distally, while the upper portion of the femoral neck is turned around the length as axis or rod [35].

Staheli also compared a control group of children to children with normal and those with spastic hemiplegia. Anteversion on the affected side was 11 degrees more than the unaffected side measuring 40 degrees. Difference was highly significant ($p \leqslant 0.001$). On the affected side, there was no sex difference found. On the unaffected side, anteversion was significantly greater in the female by 7.8 degrees, and decreased with age [32].

These influencing factors on lower extremity development are important in injury assessment. The groups to compare can be gender, race, or other. The individual variation by genetics and early activity level determine differences in bony development of pelvic landmarks, widths, acetabular version, and femoral version and lower extremity alignment.

Femoral notch

The ACL size and orientation determine width and shape of the femoral notch. Regardless of gender, smaller notches have been associated with increased rate of ACL injury. Most authors report a smaller ligament is housed in a smaller notch. However, Muneta et al used measurements from 16 Japanese knee cadavers to determine ACL cross-sectional area as it relates to notch dimensions [36]. The small notch knees did not have a thinner ACL in them.

Anderson et al evaluated 100 high school basketball players—50 male, 50 female. By magnetic resonance imaging, notch width index between the sexes were not statistically significant. With adjustments for body weight, the size of the ACL in girls was found to be statistically smaller than in boys [37]. The question remains whether or not a smaller ligament is more apt to fail. It remains unknown whether a bigger ligament is stronger. The ACL has wide ranges of ultimate load [38,39].

Plain radiographs have been used to assess the notch. Souryal and Freeman measured femoral notch X-rays for width and ratio in 902 high school athletes. The femoral notch-to-width ratio was 0.189 for noncontact injuries and 0.233 for contact. The normal was 0.231 ± 0.044 [40,41].

Shelbourne et al [42] reported on the relationship of the intercondylar width of the femur and ACL tears prospectively. Seven hundred fourteen patients underwent weight-bearing PA views as described by Rosenberg et al [43]. The mean notch width was 13.9 ± 2.2 mm for women and 15.9 ± 2.5 mm for men. Patients tore their opposite ACL much more often if notch measured < 15 mm. The incidence was ± 16 mm (4/326). There was no statistically significant difference in notch width between height groups for men and women [42]. The ratios that have been reported of the notch width divided by the femoral bicondylar width creates problems with comparison. In this study, women who were as tall as their male counterparts had statistically significantly narrower femurs for all heights. Women were found to have significantly narrower notches than men, with height and weight as covariants. After ACL reconstruction with 10-mm autografts, there was no difference in graft tear pattern between the groups, men or women.

Ireland et al compared normal to ACL injured notch measurements. The group was ACL injured (55 women and 53 men), with ACL intact and ACL uninjured (94 women and 92 men). The 294 radiographs were reviewed for notch width, femur width, and notch width ratio. Regardless of gender, individuals who possess smaller notch dimensions appear to be at greater risk for injury than individuals with larger notches [44]. A template to position the knee during acquisition of notch views was suggested to reduce the variability.

Analysis of the intercondylar notch has also been recorded by computed tomography [45] and by magnetic resonance imaging [37]. Magnetic resonance imaging scans have been analyzed for notch size and ACL volume. In 100 high school basketball players, 50 male and 50 female, Anderson et al [37] found that the size of the ACL was statistically smaller in girls than boys, but there was no significant difference between the notch width index between the sexes. However, there was no significant correlation by magnetic resonance imaging analysis between the ACL area and the notch width in males ($r = 0.177$, $p = 0.22$) or females ($r = 0.225$, $p = 0.07$).

Charlton et al [46] measured 96 knees in 48 asymptomatic subjects and found that the volume of the femoral notch was statistically smaller in women compared to men, but this difference was primarily related to height. The ACL volume was also significantly smaller in females and there was indeed a significant correlation between femoral notch volume and ACL volume, that is, smaller notches housed smaller ACLs.

Neuromuscular

Gender differences in neuromuscular activation patterns have been reported to contribute to ACL injury. Compared to males, females have been found to be less effective in stiffening their knee [47]. Maximum contraction of the knee musculature significantly decreased the anterior tibial translation in men and women comparing relaxed to contracted states. However, the percent increase in knee stiffness was significantly greater at the $p = 0.003$ level, with male percentages of 473% and females 217% [47].

Wojtys and Huston have done excellent work on the comparison of neuromuscular performance in elite male athletes, female athletes, and nonathletic females [34,48,49]. In a series of four groups, 40 elite females and 60 elite male athletes, and 40 sex-matched nonathletic controls, function testing was performed, which included isokinetic dynamometer strength and anterior tibial translation stress tests. Results of these tests revealed that the female athlete and controls demonstrated more anterior tibial laxity by arthrometry than male counterparts and less muscle strength and endurance. The female athletes take significantly longer to generate maximum hamstring torque during isokinetic testing than males. The muscle recruitment order in some female athletes was markedly different, and the quadriceps was recruited initially in response to anterior tibial translation instead of the hamstrings for initial knee stabilization [48].

Wojtys et al also looked at the effects of muscle fatigue on anterior tibial translation with findings that the muscle responses were slower with fatigue of the gastrocnemius hamstring and quadriceps muscles [34]. There was increased displacement of the tibia in the fatigued state. It was felt that fatigue play an important role in the knee injuries and physically demanding sports.

In looking at the effects of fatigue, the recruitment order of muscles did not change with fatigue, but the anterior tibial translation increased by 32.5% [34]. Comparing volleyball and basketball athletes in the normal and fatigued state, maximum knee flexion occurred earlier in run and rapid stop maneuvers when the subjects were fatigued [50]. There was later activation of vastus lateralis, rectus femoris, biceps femoris, and medial hamstrings, indicating less stability, damping, and shock absorption effect from these muscles.

A 6-week agility training program on 16 males and 16 females generated significant improvement in response time [49]. The cortical response time of medial hamstring and medial quadriceps in the isokinetic group slowed significantly—39.1 to 32.4 mseconds. However, in the agility trained group, the cortical response time significantly improved in gastroc medial hamstring and lateral quadriceps group. Agility exercises are felt to improve muscle reaction time, whereas isokinetic and isotonic strengthening programs did not.

In a running cross-cutting and side-cutting study comparing males and female, electromyography (EMG) and kinematic differences were reported [51]. The females performed these maneuvers with less knee flexion (24.6° versus 29.8°), less hip flexion (30.9° versus 39.0°), more knee valgus (11.1° versus 1.9°), and less hamstring activation (146.3 versus 135.2% maximal voluntary contraction [MVC]). In a collegiate study, the elite female athlete fired quadriceps first without full activation of hamstrings when compared to collegiate females, collegiate males, and elite males [48]. This early quadriceps activity may translate the tibia anteriorly contributing to ACL failure.

The conclusions of EMG analysis of 34 healthy collegiate soccer and basketball athletes by Rozzi et al revealed that women inherently possess greater knee joint laxity values and a longer time to detect the knee joint motion moving into extension. Further, women demonstrates superior single-legged balance ability and greater EMG peak amplitude in the area of the lateral hamstring muscle subsequent to landing and jumping. This excessive joint laxity appears to contribute to diminished joint proprioception, potentially increasing risks [52].

Shultz and Perrin [53] reported that there were differences in surface EMG assessing sex differences in neuromuscular response characteristics. Future studies with the knee under functional weight-bearing conditions controlling training and compounding variables are needed.

Chappell et al [54] found significant differences in male and female kinematics during specific jumping tasks. Women exhibited greater proximal anterior shear force than men during the landing phase. There was greater knee extension and valgus moment at the knee in women compared to males who exhibited flexion and varus knee moments. This increase in peak proximal tibial anterior shear force during stop–jump tasks in combination with findings of early quadriceps activity with fatigue places the ACL at greater risk for injury [34,49,54].

Hewett [55] has documented a reduction in these risk factors in females in response to a plyometric training program. Specifically, females decreased impact forces, increased hamstring torque (44% dominant side, 21% nondominant side), and reduced the adduction/abduction moment by nearly 50%. Further studies are needed to evaluate sex differences in neuromuscular responses, reflex muscle activation, and load about the knee joint under sports conditions.

Core stability

It has long been understood that lack of control contributes to an individual getting into a position that allows for an ACL rupture. In recent years, the realization of proximal control dictating distal function has become increasingly apparent. One concept that has been closely linked to this has been the idea of "core stability." The "core" may be operationally defined as the abdominal, back extensor, and hip musculature strength/function that contribute to stability of the lumbopelvic–hip region complex where a person's center of gravity is located and all movement begins [56]. Richardson et al [57] showed that the abdominal musculature role as a primary stabilizer of the internal and external obliques are the primary stabilizers of the trunk, and the transversus abdominus promotes lumbopelvic region stability of utmost importance for function. A study by Cresswell et al [58] gave evidence that transversus abdominus is critically important to spine stabilization. Horak et al [59], when comparing movements of lower extremity to erector spinae function, identified a temporal relationship between biceps femoris and erector spinae reaction time latency [59]. Bouisset and Zattara [60] demonstrated that hip and lower extremity activation preceded onset of upper limb acceleration.

An efficient core allows the length–tension relationship of functional agonist and antagonist to be maintained. Baratta et al [61] have also shown that antagonists provide regulated stabilizing function to distraction forces generated by the agonist muscles. An efficient "core" provides for a stable base so the lower extremity can function with an optimal kinetic chain to reduce forces and dynamically stabilize against abnormal forces. If the extremity muscles are strong and the core is weak, not enough force will be created to produce efficient movements [56]. It is these inefficient movements and abnormal agonist/antagonist relationship from an unstable "core" that set the stage for injury.

Beckman et al [62], in a study of ankle inversion injury and hypermobility, were able to show that significant latency differences in premature onset of the gluteus medius activation are seen in subjects with unilateral ankle inversion injury versus their normal controls. Bullock-Saxton et al [63] were also able to show that there is a latency reduction in gluteus maximus activation in individuals with a previous severe unilateral ankle sprain, and that these effects are on both the affected and unaffected side.

The question remains—did the distal injury cause proximal muscle activity changes, or were the proximal deficiencies causative in the ankle sprains? More specifically in regard to ACL tears, anecdotal observations have shown that weaknesses in "core strength" are seen in athletes following ACL injury. Bruce Kola, at Colorado College, has noted after ACL reconstruction a side-to-side difference that he feels exists prior to ACL injury (B. Kola, personal communication). The pattern that he has seen in many athletes are ipsilateral side weakness in hip adduction, gastroc soleus and toe flexors, and contralateral weakness in hip abductors and scapular stabilizers. A program of landing and strengthening has been done at Colorado College with great success of a reduction of injury.

In a series of 75 collegiate basketball players, 50 female and 25 male, four tests were used to determine core strength. These were the back extensor muscles tested by modified Biering-Sorensen test, a side bridge test to measure lateral trunk flexors, straight-leg abdominal lowering test, and hand-held dynamometer strength test for hip external rotation and abduction. Injuries were tracked the next season. Males performed significantly better than females on all tests. There was a correlation found between external rotation and abduction strength. Side bridging correlated with external rotation. There was a trend but no statistical significance that a weaker core related to higher injury rates in the first year of the study.

To date, no studies have prospectively analyzed measurements of "core" musculature as they relate to risk for lower extremity injury. However, preliminary results from the ongoing prospective analysis of 104 varsity collegiate athletes indicate a positive correlation between some measures of "core" stability including hip abduction and external rotation weakness and risk for lower extremity injury. Further studies with larger samples using valid and reliable measurements to assess "core stability" are necessary to further illuminate this research question. The challenge is making the strength testing efficient, portable, easy to teach, and reproducible for athletes and trainers to participate enthusiastically.

ACL research retreat consensus statement

An ACL research retreat for gender bias was held in April 2001, with participants presenting their research in areas of neuromuscular, biomechanical, hormonal, and structural. Publication of this was done, and a consensus statement of what we know, what is still unknown, and where do we need to go was published in *Clinical Biomechanics* [64]. Multicenter prospective studies to look at the multiple factors contributing to the future in the biomechanical area is to develop more valid methods of kinematic measurements and develop functionally valid tests. In the hormonal area, although there are receptors for progesterone and estrogen on the ACL, there is no definitive information of whether cyclic hormonal change can cause structural change in the ACL properties. Future studies are needed on the basic research in the area of ligament remodeling, influence of sex hormones on other ligaments, capsule, and muscle tendon structures. More valid methods of recording daily hormonal levels need to be established. In the structural factors, further studies on relationships and tests that measure structure as it relates to ACL injury across gender must be developed.

Prevention programs

Prevention programs emphasize a safe flexed, hip over knee over ankle landing pattern. Prevention programs have been implemented and have reduced injuries in athletes. From Chuck Henning in the 1980s, who implemented basketball players doing rounded turns and several step stops [65] to the ski slope where an understanding of the way to fall and control ski tips (Johnson), prevention is indeed possible [66–69]. A prevention program and risk factor book is available [10].

Hewett et al [55], in a preseason 6-week flexibility plyometric landing program, reduced the rate of knee injuries from 4.3 to 1.2 per 1000 exposures. This was significantly reduced in the trained female athlete. Further, Mandelbaum [70] has reported reduction in ACL injuries with a training program in youth soccer. In a study of youth soccer, the Prevent Injury and Enhance Performance was implemented for 15minutes two or three times per week before practice. The numbers enrolled in program were 52 teams, consisting of 1041 females, and a control group of 91 teams, consisting of 1905. The program is available at www.ACLprevent.com. Statistics per year per athlete in the control group included 32 ACL injuries for an incidence rate of 1.7 and two ACL injuries/participant with an incidence rate of 0.2 injuries/participant in the enrolled group ($p > 0.05$) . The age group of 14–18-year-old soccer athletes enrolled in the program had an 88% decrease in ACL tears.

Prevention of noncontact ACL injuries headed by Letha Griffin is a compilation of the current available prevention programs for skiing, soccer, volley ball, and basketball, and contact information for these programs is available in that publication.

In a Cincinnati study, Hewett et al [55] reported an intervention program of prospective design with athletes from 12 high schools, 43 teams. A 6-week preseason training program of plyometrics involved 1263 athletes in three groups—trained and untrained females, and a male control group. The knee injury incidence rate per 1000 exposures was significantly less in the trained compared to untrained female athletes, and approached that of male athletes, the rates being untrained female 0.43, trained female 0.12, and male athlete 0.09. The untrained female athlete had a 3.6 times higher incidence of knee injury than the trained ($p = 0.05$) and 4.8 times greater than the male athlete ($p = 0.03$).

Under the Johnson program, the skiing prevention program is available through the Vermont Safety Research, P.O. Box 85, Underhill Center, Vermont 05490, and videotape information available at 1-802-899-2126 [63].

Summary

Multiple factors are responsible for ACL tears. The key factor in the gender discrepancy appears to be dynamic, not static, and proximal, not distal. The factors involved in evaluating the female ACL are multiple. However, it is the dynamic movement patterns of hip and knee position with increased flexion and a coordinated proximal muscle firing pattern to keep the body in a safe landing position that are the most critical factors. An ACL injury at an early age is a life-changing event. We can very successfully reconstruct and rehabilitate an ACL, but we cannot stop there. We must now go into the prevention arena.

In the United States there is tremendous variation in the exposure and acquisition of skills of physical activities in our youth. Today, children are often playing inside, using computers and watching television—missing out on the opportunity to learn safe movement patterns. Therefore, physical movement classes should occur very early in life, teaching children to land safely and in control, similar to the cry of "get down, stay down" routinely heard during youth soccer. Similarly, specific strength training programs can address landing as well as foot movements during cutting in basketball. Coaches should issue stern warnings when athletes demonstrate a high-risk movement patterns such as one-leg landings, out-of-control baseline landings, or straight-leg landings. The warnings may serve to keep the athlete from "touching the hot stove again" for fear of getting burned.

No athlete feels she will be the one to get injured. Therefore, prospective analysis is likely to be received more warmly by the athletes if the program is presented with an emphasis on performance improvement rather than injury prevention. With increased participation in these programs, multiple-center analysis will have the power necessary to determine which factors significantly predispose athletes to ACL injury. The future for injury prevention is bright. We must rise to the challenge.

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