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# Play at Your Own Risk: Sport, the Injury Epidemic, and ACL Injury Prevention in Female Athletes

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This article focuses on describing anterior cruciate ligament (ACL) injury in athletes and the efficacy of implementing a neuromuscular and proprioceptive sports-specific training program to reduce the incidence of ACL ligament injuries. This article will discuss the role of the ACL, epidemiology and etiology, and the four categorical risk factors for incurring an ACL injury: anatomical, environmental, hormonal, and biomechanical. In addition, this article will discuss the mechanisms ACL injuries, as well as a comprehensive review of all of the literature that has been published with regard to the prevention or reduction of ACL injury. The article concludes that a neuromuscular training program might have a direct benefit in decreasing the number of ACL injuries in athletes.

The anterior cruciate ligament (ACL) is one of the major stabilizing intracapsular ligaments in the knee joint. This ligament prevents excessive anterior translation of the tibia on the femur. In addition, it plays a secondary role of limiting internal rotation of the tibia. It is housed in the intercondylar notch of the femur. The proximal attachment is the posterior medial surface of the lateral femoral condyle, while it attaches distally to the anterior portion of the intercondylar eminence of the tibia (Norwood, 1977). There are two distinct bundles in the ACL joint: (1) the anteromedial portion, which is taught in knee flexion and the (2) posterolateral portion which is taught with knee extension.

The ACL works collectively with the posterior cruciate ligament (PCL) to stabilize the knee during dynamic movement. The PCL is attached to the posterior portion of the intercondylar eminence of the tibia and passes forward to attach to the medial condyle of the femur. The medial collateral ligament (MCL) is attached to the medial femoral condyle and the medial surface of the tibia. The lateral collateral ligament (LCL) is attached to the lateral femoral condyle and the lateral portion of the head of the fibula The MCL and the LCL are extracapsular ligaments and provide stability to the knee joint in the frontal plane during varus and valgus loads (Rosse & Gaddum-Rosse, 1997).

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## How is the ACL Ruptured?

Injuries to the knee joint are common. Typically, ligamentous or meniscal structures are damaged while incurring a knee injury. Ligaments are usually torn when an excessive external force is applied to the limb, whereas meniscal injuries usually occur from forces generated within the limb (torsional). However, unlike most ligamentous structures in the body, the ACL ligament can be injured without an external force being applied to the knee joint. In the United States alone, approximately 250,000 ACL injuries occur on an annual basis (Chandy & Grana, 1985). This correlates to a one in 3,000 chance that an individual in the general population will sustain an ACL injury. The fiscal burden of such an injury is quite large; when considering the costs of MRI's, reconstructive surgery, postoperative bracing and rehabilitation, the average annual cost exceeds 2 billion dollars (Gottlob, Baker, Pellissier, & Colvin, 1999; Malek, DeLuca, Kunkle, & Knable 1996). In addition, the psychological impact of such an injury can be quite devastating to the individual. Typically, an athlete will miss approximately six to nine months of competitive play as a result of the ACL injury, reconstructive surgery, and rehabilitation. However, this estimate does not reflect the large dichotomy that exists when you stratify the epidemiological data for gender.

After the passage of Title IX of the Educational Amendments in 1972, allowing equal opportunity for female participation in sport, there has been an exponential surge of females participating in organized sports. With this influx in athletic participation, there have also been more injuries sustained by these females. Female athletes have a two- to ten-fold higher incidence rate of ACL injuries compared with their male counterparts. Arendt and Dick (1995) examined the increased incidence of ACL injury among NCAA Division I athletes participating in basketball and soccer over a 5 year period. The injury rate was recorded and analyzed per athlete exposure, where one practice session or game counted as an exposure. The average ACL injury rate was 0.31 per 1000 athlete exposures for female soccer and 0.29 per 1000 athlete exposures for female basketball. This is compared with 0.13 for male soccer and 0.07 for male basketball per 1000 athlete exposures. This epidemiological data for ACL injury rates points to the blatant discrepancy that exists between genders.

Complete ACL injuries can lead to chronic knee pathology, including instability, secondary injury to the meniscii and articular cartilage, and the early onset of osteoarthritis. Approximately 66% of all patients that incur a complete ACL injury incur damage to the menisci and the articular cartilage of the femur, patella, and/or tibia. This injury, coupled with the risk of secondary injury, can significantly interfere with the activities of daily living and quality of life. Having a ruptured ACL surgically reconstructed can significantly reduce the risk for secondary injury (Fetto & Marshall, 1980; Harner, Paulos, Greenwald, Rosenberg, & Cooley, 1994; Noyes, Mooar, Mattews, & Butler, 1983). Seitz, Marlovitz, Wielke, and Vecsei (1996) noted that 65% of ACL deficient patients sustained a secondary meniscal injury within 2.5 years of the initial date of injury.

Despite the most earnest efforts of orthopedic surgeons to preserve the integrity of the knee joint during ACL reconstructive surgery, individuals with reconstructed ACLs continue to report degenerative changes of the articular cartilage and the inevitable early onset of osteoarthritis. Lohmander, Ostenberg, Englund, and Roos (2004) completed a 12 year longitudinal study to follow up on female athletes that previously underwent ACL reconstruction after sustaining an injury while playing soccer. They found that 55 women (82%) had radiographic changes in their index knee and 34 (51%) fulfilled the criterion for radiographic knee osteoarthritis. The mean age for the participants involved with this study was 31. The implications of this research are ominous—hence the need to prevent these injuries from occurring in the first place.

## Mechanism of Injury

The mechanism of injury for an ACL injury has been studied extensively. There are two types of ACL injuries: contact and noncontact. Seventy percent of all reported ACL injuries are noncontact in nature, whereas the remaining 30% involve contact from an outside force such as an opposing player, a goalpost, or another object on the field or court.

The mechanism for a noncontact ACL injury in field and court sports commonly involves one step-stops, cutting tasks, sudden changes of direction, landing from a jump with inadequate knee and hip flexion (at or near full extension), or a lapse of concentration (because of an unanticipated change in the direction of play). Noncontact ACL injuries typically occur during a deceleration maneuver combined with a change of direction while the foot is in a closed chain position. While the foot is in a closed chain position and pronated, the tibia is internally rotated, and the knee is at or near full extension (range of 0–20 degrees of flexion); if the athlete attempts to change direction, the result is an excessive torsional force that can potentially strain or rupture the ACL.

With regard to downhill alpine skiing, the mechanism of injury is slightly different. Three common causes of ACL injury have been discussed in the literature (Feagin & Lambert, 1985, Feagin et al, 1987). The first is the "phantom-foot mechanism"—where a skier falls backward with the knee flexed past 90 degrees and the tibia internally rotates. The combination of a strong quadriceps contraction applying an excessive anterior force to the proximal tibia with a rigid ski boot (distally) that fails to release may lead to an ACL sprain or tear. The second mechanism involves a skier landing on the ski's tail. The stiffness of the posterior shell of the boot combined with a strong quadriceps contraction applying an excessive anterior migration of the tibia may lead to an ACL injury. The third mechanism typically involves male downhill skiers that are skiing under poor conditions and/or with high velocity. This mechanism occurs when the antero-medial edge of the ski gets caught under snow. The involved limb begins to abduct and externally rotate while the skiers' momentum carries him or her forward (Ettlinger, Johnson, & Shealy, 1995).

A study recently published by Brophy, Silvers, Gonzalez, and Mandelbaum (in press) examined the role of leg dominance in ACL injury risk among soccer athletes. The researchers hypothesized that soccer players rupture the ACL of their preferred support leg more frequently than the ACL in their preferred kicking leg, particularly in noncontact injuries. Gender results were similar. This retrospective observational study included participants that had sustained a noncontact ACL injury as a result of direct participation in soccer ($N$ = 93; 41 male, 52 female).

For noncontact ACL injuries, roughly half of the injuries occurred in the preferred kicking leg (30) and the contralateral leg (28). However, by gender, there was a significant difference in the distribution of noncontact injuries; 74.07% of males (20/27) were injured on the dominant kicking leg compared with 32.26% (10/31) of females ($p < .002$). The researchers found that females are more likely to injure the ACL in their supporting leg whereas males tend to injure their kicking leg. This research suggests that limb dominance does serve as an etiologic factor with regard to ACL injuries sustained while playing soccer. If follow-up studies confirm that females are more likely to injure their preferred supporting leg, future research should investigate the cause for this discrepancy, which could result from underlying gender based anatomical differences as well as differences in neuromuscular patterns during cutting maneuvers or kicking. This information could potentially optimize prescribed prevention programs with respect to gender.

## Risk Factors

A consensus group comprised of physicians, surgeons, physical therapists, and certified athletic trainers met in Hunt Valley, Maryland in 1999 to discuss the epidemic of ACL injuries in the female athlete. Four categorical risk factors have been identified while attempting to determine the etiology leading to the increased rate of ACL injuries in the female athlete (Griffin et at., 2000). The risk factors were examined independently to determine the primary factor(s) involved in the etiology of ACL injuries. These include:

1. Anatomy
2. Hormones
3. Environment
4. Biomechanical and neuromuscular

This group of researchers reconvened in Atlanta, Georgia in January 2005 to reevaluate the identified risk factors and to determine what progress has been made since the inaugural meeting in 1999 (Griffin et al, 2006).

### Anatomy

With regard to the anatomical risk factors, there are multiple differences that exist between genders. The typical female demonstrates increased femoral anteversion, an increased Q angle, excessive tibial torsion, and excessive subtalar pronation compared with her male counterpart. In addition, the size of the intercondylar notch in the femur and the actual diameter of the ACL itself are smaller in females. Impingement of the ACL against the lateral portion of the medial intercondylar notch has been proposed as a potential anatomic cause of ACL injury. Typically, men demonstrate a wider U-shaped intercondylar notch whereas women demonstrate a more narrow cresting-wave (A-shape) notch (Jacobsen, 1976; Kennedy, Wineberg, & Wilson, 1974). It has been suggested that as a result of the more narrow geometry of the female intercondylar notch, perhaps the ACL is impinged on the medial border of the lateral femoral condyle when combined with a valgus load (Nisell, 1985). However, the cross sectional area of the ACL is significantly smaller in women than in men.

Perhaps, in the female athlete, having a smaller ACL in a narrow intercondylar notch provides some protective benefit to the ACL. No studies to date have indicated that there is a direct correlation between ACL size and ACL injury rates. Shelbourne, Davis, and Klootwyk (1998) studied patients who underwent autogenous patella tendon graft ACL reconstructions and divided them into two groups: narrow notches and wide notches. Intercondylar notches greater than 16 mm were defined as wide and those less than 15 mm were defined as narrow. The notch width in female patients was narrower than their male counterparts of the same height. The results, however, did not indicate any correlation between gender and the rate of injury to the contralateral ACL or with the rerupture rate. Anatomic risk factors might play a small role in the incidence of noncontact ACL injury; however, they may have a more direct impact when the body is dynamically moving. Future studies assessing incidence rates in relation to anatomic risk factors and multiplanar dynamic movement patterns are necessary.

## Environment

Environmental risk factors are extrinsic factors that include prophylactic and functional knee bracing, footwear choice, playing surface, and weather (climate).

***Prophylactic and functional knee bracing.*** No conclusive studies demonstrate the effectiveness of functional knee braces in preventing noncontact ACL injuries. A study completed by Deppen and Landfried (1994) examined the usage of prophylactic knee bracing in high school football players. The injury rates of eight high school football teams were analyzed comparing those who wore prophylactic knee braces to those who did not wear the knee braces. Over a four year period, 23 knee injuries occurred in 21,640 exposures in the braced group compared with 26 knee injuries in 19,484 exposures in the nonbraced group. There was no statistically significant difference in the rate of knee injury or the severity of injuries between the two groups. Due to the financial implications of prophylactic bracing, and the apparent similarities between the rates of injury in the braced and nonbraced group, it is recommended that the medical community does not advocate the use of prophylactic bracing in this population.

***Footwear.*** In 1974, Torg, Quedenfeld, and Landau developed a quantitative measurement entitled “release coefficient” to describe the force-to-weight ratio of shoe surface interaction. This work was reinforced by Heidt et al. (1996), who found that 73% of the 15 different types of athletic shoes tested demonstrated an “unsafe” or “probably unsafe” rating. When considering shoe design, it is important to remember that although an increased friction coefficient may enhance performance, it may also inadvertently increase ligamentous injury. Ekstand and Nigg (1989) noted that there is an optimal range to be incorporated in shoe design—one that will minimize rotational friction to avoid injury yet optimize transitional friction to allow peak performance when performing activities such as cutting and decelerating.

***Playing surface.*** Playing surface and shoes must be considered when determining whether these factors can independently increase the rate of noncontact ACL injuries in women. A recent study examining the incidence of ACL injury in European team handball found that injury rates on wooden floors (parquet, generally having lower friction) are less frequent compared with those occurring on artificial floors (generally having higher friction). A total of 174 ACL injuries were recorded over eleven seasons. The floor types for all games were recorded; wood or artificial. A total of nine injuries occurred among men (incidence: .24 ± .09) and 44 among women (.77 ± .04). Among men, four injuries occurred on wooden floors (.32 ± .13) and five injuries occurred on artificial floors (.20 ± .12). Among women, eight injuries occurred on wooden floors (.41 ± .09) and 36 on artificial floors (.96 ± .04). The results indicate that the risk of ACL injury for women is higher compared with men on artificial floors than on wooden floors.

Uneven playing surfaces may play a role in ACL incidence rates. Huston, Vibert, Ashton-Miller, and Wojtys (2001) reported that patients reported landing or stepping on an uneven surface (inconsistency in grass or another player) at the time of injury. In addition, irrigation of the field may affect the rate of ACL injury. Scranton, Jr, Lanzer, Ferguson, Kirkman, and Pflaster (1998) identified 61 noncontact ACL injuries in 22 National Football League teams over the course of four seasons. The variables of surface, shoe type, playing conditions, and shoe spatting were identified for each ACL injury. Forty noncontact injuries occurred in conventional cleated shoes on natural grass, and 21 occurred on an artificial surface. Injury rates on game day exceeded that of practice: (47.5%) occurred during game-day exposures despite the fact that the practice versus game-day exposure rate was 5:1. Of these injuries, 95.2% occurred on a dry field.

***Weather (climate).*** Orchard and Powell (2003) analyzed at 5,910 NFL team games to determine whether a correlation existed between knee and ankle sprains, playing surface, and the weather conditions on the day of the game. The researchers found a reduced risk of significant ankle sprains for games in natural grass stadiums compared with indoor domes (using AstroTurf). In addition, there was also lower incidence of significant knee sprains on grass compared with domes which was directly related to cold and wet weather on grass. In open (outdoor) AstroTurf stadiums, cold weather was associated with a lower risk of ACL injuries compared with hot weather in the same stadiums. The ACL incidence rate was lower during the later (cooler) months of the season in open stadiums (both AstroTurf and natural grass) but not in domes. The researchers concluded that cold weather is associated with lower knee and ankle injury risk in outdoor stadiums (both natural grass and AstroTurf). This reduction is most directly related to lower shoe-surface friction coefficents.

## Hormones

There has been increasing speculation that the hormonal changes that occur throughout the month may increase a female athlete's susceptibility to ligamentous injury (Samuel, Butkus, Coughlan, & Bateman, 1996, Sciore, Frank, & Hart, 1998). The menstrual cycle can be subdivided into three distinct phases that are based on a mean cycle of 28 days. The follicular phase (days 1–9) represent low levels of both progesterone and estrogen until the late follicular phase, at which time estrogen levels spike. The estogen spike continues in the ovulatory phase (days 10–14). During the luteal phase (days 15–28 progesterone rises and, in the second half, relaxin rises as well (Hama, Yamamuro, & Takeda, 1976). The fluctuation of progesterone, estrogen, and relaxin during the menstrual cycle has been studied to determine whether there is a correlation with integrity of the ACL. Estrogen, progesterone, and relaxin receptor sites have been found to be present within the ACL (Galey, Arnold, Konieczko, & Cooney, 2000).

The increase of estrogen and relaxin hormones have been shown coincide with a subsequent 40% decrease in the rate of collagen synthesis. Yu, Liu, Hatch, Panossian, and Finerman (1999) and Yu, Kirkendall, and Garrett (2002) simulated the effects of 17-β estradiol on the rate of cell proliferation and precollagen levels in female ACL fibroblasts throughout the menstrual cycle in an in vitro study. Samples of a healthy female subject's ACL were treated with17-β estradiol on various days of the menstrual cycle: 1, 3, 7, 10 and 14. Cell proliferation and precollagen levels were used to determine the rate of collagen synthesis. Yu found an inverse correlation between the ACL fibroblasts and the concentration of 17-β estradiol. As the 17-β estradiol dosage increased, the number of fibroblasts on the ACL decreased in a dose dependent fashion. The researchers proposed that 17-β estradiol released during the normal menstrual cycle could potentially effect the incidence of ACL injury in female athletes due to its direct effect on collagen synthesis. Slauterbeck, Clevenger, Lundberg, and Burchfield (1997) used a rabbit model to determine the effects of estrogen on the load to failure of the animal ACL. They demonstrated a decrease in tensile properties of the ACL and a subsequent decrease in the ACL failure load of the estrogen treatment group (rabbits) compared with the control. With regard to ACL injury in relation to phase of the cycle, Wojtys, Huston, Lindenfeld, Hewett, and Greenfield (1998) noted a statistically significant increase in ACL injury while athletes were in the ovulatory phase (days 10–14) of the menstrual cycle. Mykelbust et al. (1998), in contrast to Wojyts et al.'s findings, found that the ACL injury rate decreased between days 8–14. There is room for speculation when comparing the collection methods for the hormonal assays and the researcher's method of obtaining them (saliva, urine, or blood). Furthermore, an accurate account of menstrual status from an athlete in a retrospective fashion may lack accuracy. Therefore, no conclusive evidence links an increase in ACL injury to any predictable time within the menstrual cycle. Further studies investigating menstrual cycle phases using larger sample sizes and independent hormonal assays at various times throughout the menstrual cycle are encouraged.

## Biomechanical and Neuromuscular

In regard to environmental, anatomic, and hormonal risk factors, there is no conclusive evidence that would indicate any one single risk factor directly correlating with an increase in anterior cruciate ligament injuries in the female athlete population. Therefore, the emphasis has turned to biomechanical risk factors and the utilization of neuromuscular and proprioceptive intervention programs to address potential biomechanical deficits.

Neuromuscular control of the knee involves a complex interaction between the afferent and efferent neurological system and the muscles that control the knee joint (Ghez, 1991). The feedforward mechanism is a system that is used to anticipate external forces or loads to stabilize the joint, thus protecting the inherent structures. Proprioception is described as the acquisition of stimuli by peripheral receptors in addition to the conversion of mechanical stimuli to a neural signal that is transmitted along afferent pathways of the sensorimotor system. Proprioception does not include CNS processing of the incoming afferent signal, nor does it include control of efferent (outgoing) motor signals. However, this "proprioceptive" information is crucial for optimal motor performance. It is delivered to every motor control center and is used to garner information regarding joint position and kinesthesia (joint motion) in space to elicit active and reflexive movement. Neuromuscular control is defined as the unconscious efferent response to an afferent signal regarding dynamic joint stability. The afferent proprioceptive signals that elicit motor control can be distinguished by their role: feedback or feedforward. Feedback mechanisms are a result of afferent input (force to the joint) and are reflexive in nature. The time to elicit such a reaction is longer, thus it is thought to be more heavily involved with maintaining posture and slow movement. Feedforward mechanisms are a result of preactivated preparatory activation of muscle (Lephart, Riemann, & Fu, 2000). Several research studies have indicated that proprioceptive activities may play a major role in injury reduction (Besier, Lloyd, Cochrane, & Ackland, 2001; Bjordal, Arnly, Hannestad, & Strand, 1997; Cerulli, Benoit, Caraffa, & Ponteggia, 2001; Lloyd, 2001; Silvers & Mandelbaum, 2001).

Muscular strength and recruitment patterns are crucial to knee stability. Quadricep to hamstring strength ratios have been examined thoroughly in the literature. The quadricep serve as an antagonist to the ACL—due to its attachment site, the quadriceps increase the anterior shear force on the tibia. The hamstrings act as an agonist to the ACL; as they reinforce the ligament by preventing the excessive anterior translation of the tibia. If the hamstrings demonstrate weakness or a delay in contraction time in comparison with the quadriceps, the ACL may be at an increased risk for injury and subsequently lead to tensile failure (Decker, Torry, Noonan, Riviere, & Sterett, 2002).

Landing from a jump with minimal hip and knee flexion increases the load transmitted to the knee and increases the shear force from the quadriceps; thus stressing the ACL (Woo, Hollis, & Adams, 1991). More et al. (1993) studied a cadaveric model that incorporated quadriceps and hamstrings muscle loads to simulate the squat exercise. When the hamstring was loaded, anterior tibial translation during flexion was significantly reduced and in addition to a reduction in internal tibial rotation during flexion. Hamstrings muscle activity during a squat functions synergistically with the anterior cruciate ligament to provide anterior knee stability. McLean, Neal, Myers, and Walters (1999) compared knee kinematics and gender in 30 high-performance athletes performing side-cutting maneuvers. Women displayed increased intertrial variability for axial internal rotation patterns during cutting compared with men. Gender, however, was not the main determining factor. Instead, the differences in axial rotation were directly related to level of experience. It is important to note that these subjects were high-performance athletes; this might have resulted in a selection bias.

On a follow-up study, McLean, Huang, Su, and Van Den Bogert (2004) studied 10 male and 10 female athletes performing cutting maneuvers with random perturbations at initial contact ($n$ = 5000). Injury to the ACL in the sagittal plane was defined as incurring an anterior drawer force greater than 2000 N. The researchers found that neuromuscular perturbations produced significant increases in external knee anterior force, valgus moments and internal rotation moments. During the study, the anterior drawer force never exceeded 2000 N in any model. Valgus loads reached values that were high enough to rupture the ligament, occurring more frequently in females than in males. McLean, et al. (2004) concluded that sagittal plane knee joint forces cannot rupture the anterior cruciate ligament during sidestep cutting, primarily due to the fact that the muscle and joint mechanics and external ground reaction forces in this plane protect the upward limit of ligament loads. They suggested that valgus loading is a more likely injury mechanism, especially in females.

In contrast, Malinzak, Colby, Kirkendall, Yu, and Garrett (2001) compared knee-motion patterns in male and female recreational athletes. Three-dimensional coordinates and EMG data were collected for knee flexion–extension, valgus–varus, and internal–external rotation angles. Female athletes demonstrated less knee flexion and greater knee valgus when landing from a jump and with cutting maneuvers. The study also determined that female athletes demonstrated greater quadriceps activity (EMG analysis) in concert with decreased hamstring activity. In addition, the frequency and intensity of hamstring activity was less in females versus males. Female athletes typically contracted their hamstring fibers 50 ms slower than their male counterparts (200 ms for females vs. 150 ms. for males) and with less intensity (55.2% females vs. 71.8% in males at initial contact).

## Prevention

ACL injury-prevention programs focusing on skiing, basketball, European team handball, and soccer have been performed in the past with results ranging in an overall reduction of severe ACL injuries from 60 to 89% (Kirkendall & Garrett, 2000).

Henning and Griffis (2000) implemented a prevention study in two Division I basketball programs over a course of 8 years geared at changing player technique—stressing knee flexion upon landing, using accelerated rounded turns, and deceleration with a multistep stop. He noted an 89% reduction in the rate of occurrence of ACL injuries in his intervention group.

Caraffa, Cerulli, Projetti, Aisa, and Rizzo (1996) implemented a proprioceptive balance training program using 600 semiprofessional and amateur soccer players in Italy. The study consisted of a 20-min training program divided into 5 phases of increasing difficulty. The prospective study was completed over the duration of three complete soccer seasons. Caraffa found an incidence rate of 1.15 ACL injuries per team per year in the control group compared with a .15 incidence rate in the trained athletes. These ratios demonstrate an overall 87% decrease in ACL injuries compared with the control group.

Hewett, Lindenfeld, Riccobene, and Noyes (1999) completed a prospective analysis of 1,263 male and female athletes of various sports using a neuromuscular training program. They used a 6-week intervention program consisting of stretching, plyometrics, and weight training with emphasis on proper alignment and technique. The group noted that the incidence of serious knee injury was 2.4–3.6 times higher in the untrained group compared with the trained group. When examining the rate of noncontact ACL injuries, five untrained female athletes sustained ACL injuries (relative injury incidence 0.26), no trained females sustained an ACL injury (0), and one male athlete sustained an ACL injury (0.05).

Ettlinger, Johnson, and Shealy (1995) implemented the "guided discovery" technique in Vermont that focused on avoiding high-risk behavior and positioning (i.e., "phantom foot"), recognizing potentially dangerous skiing situations, and responding quickly to unfavorable conditions. During the 1993–1994 ski season, 4,700 ski instructors and patrollers completed the comprehensive training program at 20 ski areas throughout the United States. As a result, the rate of serious knee injuries decreased by 62% among the trained individuals compared with those who did not participate in the training program.

Heidt et al. (2000) studied 300 female adolescent soccer players between the ages of 14 and 18 years of age over a 1 year period. Forty-two athletes participated in the Frappier Acceleration Training Program, a 7-week preseason training program consisting of strength training, flexibility, sports-specific cardiovascular exercise, plyometrics, and sports-cord drills. He found that the trained group incurred a lower percentage of ACL injuries (2.4%) compared with the age-matched control group (3.1%).

Myklebust, Maehlum, Holm, and Bahr (1998) instituted a proprioceptive training program for elite female team handball players. This 5 phase training program consisted of floor exercises, wobble-board activities, and a balance mat performed 2–3 times a week over the course of 5–7 weeks preseason and once a week in season. Fifty-eight teams participated (855 players) in the first season (1999–2000) and 52 teams (850 players) participated in the second season (2000–2001). Sixty teams (942 players) in the 1998–1999 season served as the control. There were 29 ACL injuries in the control season, 23 ACL injuries in the first intervention season, and 17 injuries in the second intervention season.

Mandelbaum et al. (2005) developed the Santa Monica PEP ACL Prevention program. This program was used with two age cohorts: 14- to 18-year-old and 18- to 22-year-old female soccer athletes. The program consisted of a 20 minute warm-up protocol to precede the normal training session. In the 2000 soccer season, a total of two ACL tears confirmed by MRI were reported for the intervention group for an incidence rate of 0.05 ACL injuries/athlete/100 exposures. Thirty-two (32) ACL tears were reported for the control group: an incidence rate of 0.47 ACL injuries/athlete/100 exposures. These results indicate an 88% overall reduction of ACL injury per individual athlete compared with skill- and age-matched control athletes. In Year 2 (2001) of the study, four ACL tears were reported in the intervention group, with an incidence rate of 0.13 injuries/athlete per 1,000 exposures. Thirty-five ACL tears were reported in the control group, with an incidence rate of 0.51 injuries/athlete/1,000 exposures. This corresponds to an overall reduction of 74% in ACL tears in the intervention group compared with an age- and skill-matched control group in Year 2 (Mandelbaum et al.)

This 2005 study by Mandelbaum et al. was followed by a randomized, controlled trial using the PEP Program in Division I NCAA Women's Soccer Teams in the 2002 Fall season (Gilchrist et al. 2008). Sixty-one teams with 1,429 athletes completed the study; participating athletes were divided into 854 athletes on 35 control teams and 575 athletes on 26 intervention teams. No significant differences were noted between intervention and control athletes with regard to age, height, weight, or history of past ACL injuries. After using the PEP Injury Prevention program during one season, there were seven ACL injuries in the intervention athletes (IA) compared with 18 in control athletes (CA), 0.14 vs. 0.25 ($p$ = .15). There were no ACL injuries reported in IA during practices compared with 6 in CA (0.10; $p$ = .01). Noncontact ACL injuries in the CA group occurred at over three times the rate of the IA group (0.14 vs. 0.04; $p$ = .06). Control athletes with a prior history of ACL injury suffered a reoccurrence 5 times more frequently than the IA group (0.10 vs. 0.02; $p$ = .06); this difference reached significance when limited to noncontact ACL injuries during the season (0.06 vs. 0.00; $p$ < .05). There was a significant difference in the rate of ACL injuries in the second half of the season (Weeks 6–11; IA 0.00 vs. CA 0.18; $p$ < .05). This would support the concept that it takes approximately 6 to 8 weeks for a biomechanical intervention program to impart a neuromuscular effect (Gilchrist et al.).

Steffen, Myklebust, Olsen, Holme, and Bahr (2008) from the Oslo Sports Trauma Research Center also attempted to reduce the incidence of ACL injury by using a set of exercises known as the "11." It was a cluster-randomized controlled trial to test the efficacy of the "11" on injury risk in female soccer players (IA, 59 teams, $n$ = 1,091) compared with a control group (CA, 54 teams, $n$ = 1,001). The "11" was a 15-min warm-up program for core stability, lower extremity strength, neuromuscular control, and agility used over an 8-month season. A total of 396 players (20%) sustained 483 injuries. There was no difference in overall injury rate between the IA (3.6 injuries/1000 hr, confidence interval (CI) 3.2–4.1) and CA (3.7, CI 3.2–4.1; RR = 1.0, CI 0.8–1.2; $p$ = .94) nor in the incidence for any type of injury. The training program was used during 60% of the soccer training sessions in the first half of the season, but only 14 out of 58 intervention teams completed more than 20 prevention training sessions. The researchers noted no effect of the injury prevention program on the injury rate secondary to the exercises, perhaps, not being specific enough to address the biomechanical deficiencies present in this population and the low compliance with the program.

To address the compliance issue and perhaps, some of the shortcomings in the exercises initially selected for the "11" protocol, the researchers reconvened and restructured the program to the "11+." Soligard et al. (2008) completed a cluster, randomized controlled trial in 125 football clubs from the south, east, and middle of Norway: 65 clusters in the intervention group (IA) and 60 in the control group (CA) followed the protocol for one league season (eight months). There were 1,892 female players ages 13–17 (1055 IA; 837 CA). A comprehensive warm-up program (11+) was used to improve strength, awareness, and neuromuscular control during static and dynamic movements. During the season, 264 players had relevant injuries: 121 players in the intervention group and 143 in the control group (rate ratio 0.71, 95% confidence interval 0.49–1.03). In the intervention group there was a significantly lower risk of injuries overall (0.68, 0.48–0.98), overuse injuries (0.47, 0.26–0.85), and severe injuries (0.55, 0.36–0.83). Though the primary outcome of reduction in lower extremity injury did not reach statistical significance, the risk of severe injuries, overuse injuries, and injuries overall was reduced.

**Table 1 ACL Injury-Prevention Studies**

| Author/Journal | Title | Sport |
|---|---|---|
| *Caraffa et al. Knee Surg Sports Traumatol Arthrosc. 1996;4(1):19–21 | Prevention of ACL injuries in soccer. A prospective controlled study of proprio training | Soccer semi-pro and amateur males N = 600 in 40 teams (20 int/20 C) |
| *Ettlinger, Johnson et al. Am J Sports Med. 1995 Sep-Oct; 23(5):531–7 | A method to help reduce the risk of serious knee sprains incurred in alpine skiing. | Alpine skiing N = 4,000 ski personnel in 20 ski areas |
| *Gilchrist, Mandelbaum, et al, Am J sports Med. 2008 36: 1476–1483. | ACL injury prevention in the Division I NCAA Female Soccer athlete | Soccer U-18 to U-22: 561 Div I NCAA females (61 universities) |
| Henning et. al (abstract only) Mid-America Center for Sports Medicine, 1990 | Injury Prevention of the Anterior Cruciate Ligament (videotape) | Basketball females |
| *Mandelbaum, Silvers et al, Am J Sports Med. 2005 Jul; 33(7):1003–10. | Prevention of ACL injury in the female soccer athlete: two-year follow-up | Soccer U-14 to U-18 N = 1,041(year 1) & 844 (year 2) females |
| *Myklebust et al Clin J Sport Med. 2003 Mar; 13(2):71–8 | Prevention of ACL's in female handball: a prospective study over 3 seasons | European Team Handball N = 900 female D I–III |
| Pfeiffer, Shea et al AOSSM Specialty Day, San Francisco, CA 2004 | Effects of a knee ligament injury prevention (KLIP) exercise program in women. | Soccer, VB, BB HS females, n = 577 int., n = 862 control |
| Söderman et al. Knee Surg Sports Traumatol Arthrosc. 2000; 8(6):321. | Balance training: prevention of injuries of the LE in female soccer players | n = 121 Int., n = 100 C; only 62 Int and 78 C completed study |
| *Hewett et. al. Am J Sports Med. 1999 Nov–Dec;27(6):699-706 | The effect of NM training on the incidence of knee injury in female athletes | N = 1,263, male ( n = 434) and female, BB, VB and soccer |
| Heidt et al. Am J Sports Med. 2000 Sep–Oct; 28(5):659–62 | Avoidance of soccer injuries with preseason conditioning | 300 female soccer players |
| *Olsen, Myklebust et al. BMJ. 2005 Feb. 330(7489): 449. | Prevention of knee and ankle injuries in youth team handball | Team handball (123 teams) N = 1,837: 1,586 female; 251 male |
| Wedderkopp, et al. Scand J Med Sci Sports. 2003 Dec; 13(6):371–5 | Comparison of 2 intervention programmes in female players in European handball | European team handball, 236 females (17–18 years), 20 teams |
| Steffen K, Myklebust G, et. al. Scand J Med Sci Sports. Jan, 2008 | Preventing injuries in female youth football—a cluster-randomized controlled trial | N = 2,092, 113 teams. IG = 59 (1,091 players); CG = 54 (1,091 players) |
| T. Soligard, G. Myklebust, et. al. BMJ December, 2008, 337: a2469 | Comprehensive warm-up programme to prevent injuries in female footballers. | Norwegian female soccer players: 1892 (1055 IA; 837 CA) |

*Indicates sufficient power.

**Table 1 (continued) ACL Injury-Prevention Studies**

| Duration | Randomized | Outcome |
|---|---|---|
| 3 season intervention (preseason) | Prospective non-randomized | 87% ↓ in noncontact ACL injury—1.15/team/season C vs. 0.15/team/season in Int. ($p < .001$) |
| 1 year intervention with 2 years historic control | Prospective non-randomized | Knee sprains ↓ 62% vs. unperturbed group who had no improvement during the study period. |
| 1 year intervention | Yes | 14 ACL's reported: 0.43 untrained vs. 0.12 trained. Untrained group 3.6–4.8 ↑ inj. rate over season. |
| 8 years | Prospective non-randomized | 89% decrease in non-contact ACL injury in female basketball athletes. |
| 2 years | Prospective non-randomized | Injury rates Year 1: 88% reduction in NC ACL injury, Year 2: 74% Reduction in NC ACL injury |
| 3 year intervention—5 phase program | Prospective non-randomized | Injury ↓ Intervention (OR: 0.06 [0.01–0.54]) vs. C–Overall 53.8 and 61.5% ↓. |
| 2 year intervention over 9 weeks—15 minutes, twice weekly | Prospective non-randomized | 6 NC ACL injuries: 3 intervention and 3 control = No effect |
| 1 season intervention, 10–15 min.sessions; total: 65 ± 19 sessions | Prospective randomized | No dec. in primary traumatic injuries to the lower extremities. 4 of 5 ACL injuries occurred in the intervention group. |
| 6 week int +1 year monitoring, 60–90 min/day, 3 days/week | Prospective non-randomized | 14 ACL's reported: 0.43 untrained vs. 0.12 trained. Untrained group 3.6 - 4.8 ↑ inj. rate over season. |
| 7 week preseason intervention, 1 year monitoring, 3 days/week | Prospective non-randomized | 61.2% injuries in knee/ankle. 2.4% injury rate in intervention vs. 3.1 in control |
| 15–20 min for 8 months: 15 consecutive sessions and then 1/week | Randomized controlled cluster trial | 129 acute; 81 in CG (0.9 , 0.3 train, 5.3 match) vs. int 48 injuries (0.5, 0.2 train, 2.5 match). 80% ↓ of ACL's. |
| 10 month intervention (one season) | Randomized controlled cluster trial | Ankle injuries ↑ CG (2.4 vs. 0.2). Five knee sprains and one knee "luxation" in CG vs. 1 knee sprain in Int Group. |
| 8 month intervention (one season) | Randomized controlled cluster trial | IG (3.6 injuries/1000 hr) & CG (3.7, CI 3.2–4.1; RR = 1.0). Only 14 out of 58 IA completed > 20 sessions. |
| 8 month intervention (one season) | Randomized controlled cluster trial | IG ↓all injuries (0.68, 0.48 to 0.98), overuse injuries (0.47, 0.26 to 0.85), & severe injuries (0.55, 0.36 to 0.83). |

This indicates that a structured warm-up program can prevent injuries in young female football players.

The similarities between the aforementioned intervention studies described are numerous. A summary of the programs is included in Table 1.

An emphasis on proper landing technique, that is, landing softly on the forefoot and rolling back to the rearfoot; engaging in knee and hip flexion upon landing and with lateral (cutting) maneuvers; avoiding excessive genu valgum at the knee upon landing and squatting; increasing hamstring, gluteus medius, and hip abductor strength; and addressing proper deceleration techniques are activities that seem to be inherent in each of the aforementioned ACL prevention protocols. The relation of these components to specific risk factors for ACL injury has been summarized in Table 2.

**Table 2 Intervention Stategies to Decrease ACL Injury**

| Position | Intervention strategy | How? |
|---|---|---|
| Extended knee at initial contact | Increase knee flexion | Concentric HS control and soft landing |
| Extended hip at initial contact | Increase hip flexion | Iliopsoas and rectus fem. control and soft landing |
| Excessive anterior translation | Increase gluteal and core/trunk control | Teach knee over midfoot position. Deceleration in controlled in sagittal and frontal plane. |
| Knee valgus with tib–fem loading | Address dynamic control; decrease dynamic valgus | Lateral hip & gluteal control upon landing |
| Balance deficits | Proprioception drills | Dynamic balance training |
| Skill deficiency | Improve agility | Agility drills to address deceleration techniques and core stability |

## Conclusion

The research discussed in this article forces the medical community at large to pose the following questions:

- What is the true mechanism for ACL injury, and is it sport specific?
- Is the mechanism for ACL injury gender specific, or does it follow a similar biomechanical pattern?
- Does fatigue negate the preventative benefit of performing an ACL injury prevention program?
- How do the successful ACL injury prevention programs work, and what are the common biomechanical threads between them?

These studies demonstrate the critical need for further randomized clinical trials on the relevance of fatigue, age of implementation, and timing of a neuromuscular injury prevention program, as well as the role of fatigue with regard to injury.

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