Reducing the Risk of Noncontact Anterior Cruciate Ligament Injuries in the Female Athlete

Sue D. Barber-Westin, BS; Frank R. Noyes, MD; Stephanie Tutalo Smith, MS; Thomas M. Campbell, BA

Abstract: High school and collegiate female athletes have a significantly increased risk of sustaining a noncontact anterior cruciate ligament injury compared with male athletes participating in the same sport. This review summarizes the current knowledge of the risk factors hypothesized to influence this problem, and the neuromuscular training programs designed to correct certain biomechanical problems noted in female athletes. The risk factors include a genetic predisposition for sustaining a knee ligament injury, environmental factors, anatomical indices, hormonal influences, and neuromuscular factors. The greatest amount of research in this area has studied differences between female and male athletes in movement patterns during athletic tasks; muscle strength, activation, and recruitment patterns; and knee joint stiffness under controlled, preplanned, and reactive conditions in the laboratory. Neuromuscular retraining programs have been developed in an attempt to reduce these differences. The successful programs teach athletes to control the upper body, trunk, and lower body position; lower the center of gravity by increasing hip and knee flexion during activities; and develop muscular strength and techniques to land with decreased ground reaction forces. In addition, athletes are taught to preposition the body and lower extremity prior to initial ground contact to obtain the position of greatest knee joint stability and stiffness. Two published programs have significantly reduced the incidence of noncontact anterior cruciate ligament injuries in female athletes participating in basketball, soccer, and volleyball. Other programs were ineffective, had a poor study design, or had an insufficient number of participants, which precluded a true reduction in the risk of this injury. In order to determine which risk factors for noncontact anterior cruciate ligament ruptures are significant, future investigations should include larger cohorts of athletes in multiple sports, analyze factors from all of the major risk categories, and follow athletes for at least one full athletic season. Future risk assessment studies should incorporate reactive tasks under more realistic sports conditions.

Keywords: ligament; noncontact; neuromuscular; female
Methods
We used the Medline database to search the literature (English language) for articles under the topics “ACL prevention,” “ACL injury risk factors,” “neuromuscular retraining,” and “ACL noncontact injuries” over a 15-year period from 1994 to 2009. Each article considered relevant was read in full, and references were cross-checked to ensure that other relevant articles were not missed from this review.

Risk Factors for ACL Ruptures
Despite many investigations that have been conducted on potential risk factors for noncontact ACL ruptures, our review found that definitive conclusions could not be reached for either men or women regarding what factor(s) may predispose an athlete to this injury. The majority of studies published have either examined a small sample size of each gender (therefore containing insufficient power to avoid a type II statistical error), only focused on one possible risk category, or examined neuromuscular characteristics in a controlled laboratory environment instead of reactive or actual playing conditions. Nonetheless, a brief discussion of the potential risk factors (Table 1) is important to understand what variables may be altered or improved through training to reduce the risk of this injury.

Few studies have been conducted to determine the effect of genetics and environmental factors on noncontact ACL injuries, and therefore, no conclusion may be reached at present regarding these factors. Some researchers believe that shoe surface interaction may affect ACL injury risk, both directly and indirectly. The direct effect is through higher traction, which may transmit excessive loads to the knee during activities such as cutting and pivoting. The indirect effect is through alterations in neuromuscular movement patterns as the athlete attempts to adapt to differences in shoe and surface factors. In terms of prophylactic knee bracing, no study to date has demonstrated a significant reduction in the incidence of ACL injuries in normal healthy athletes with any commercially available knee brace. Only 2 epidemiologic investigations have been published on this topic, both of which followed male football players only.

Table 1. Potential Major Risk Factors for Anterior Cruciate Ligament (ACL) Injury

<table>
<thead>
<tr>
<th>Gender</th>
<th>Category</th>
<th>Risk Factor</th>
<th>Summary of Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males and Females</td>
<td>Familial</td>
<td>Genetics, possibly related to anatomical structures (size intercondylar notch)</td>
<td>Only 2 studies published to date, no conclusion can be reached</td>
</tr>
<tr>
<td>Males and Females</td>
<td>Environmental</td>
<td>Climate conditions</td>
<td>Too few studies published for conclusions, shoe-surface interaction may affect ACL injury risk, further investigations required</td>
</tr>
<tr>
<td>Females</td>
<td>Anatomical</td>
<td>Q-angle</td>
<td>Conflicting study designs and published data, no definite evidence that any anatomic risk factor is associated with increased risk ACL injury</td>
</tr>
<tr>
<td>Females</td>
<td>Hormonal</td>
<td>Acute fluctuations of estrogen and progesterone during the menstrual cycle</td>
<td>There appears to be an uneven distribution of ACL injuries in the follicular phase of the menstrual cycle, but more data required before definitive conclusions may be reached</td>
</tr>
<tr>
<td>Females</td>
<td>Neuromuscular/ Biomechanical</td>
<td>Movement and muscle activation patterns Ground reaction forces Knee adduction/abduction moments Knee and hip flexion angles during landing, jumping, cutting, pivoting Muscle strength Knee joint stiffness</td>
<td>Significant differences have been documented between males and females in multiple neuromuscular indices (Table 2)</td>
</tr>
</tbody>
</table>
Reducing the Risk of Noncontact ACL Injuries in the Female Athlete

Inherent anatomic differences between genders have been proposed as being responsible or partially responsible for the disparity in noncontact ACL injury rates. Although evidence exists to support differences between men and women in many of these factors, including quadriceps femoris angle (Q angle), femoral anteversion, tibial torsion, foot pronation, size of the intercondylar notch size, and size of the ACL itself, no investigation has demonstrated that these differences alone are responsible for an increased risk of noncontact ACL injuries in female athletes.

Uhorchak et al measured height, weight, body mass index (BMI), condylar width, notch width, eminence width, tibial width, notch width index, generalized joint laxity, anterior-posterior displacement on knee arthrometer testing, isokinetic quadriceps and hamstrings concentric and eccentric strength, and hamstrings flexibility in a group of 859 West Point cadets (120 women, 739 men) upon their entrance into the academy. The cadets were followed up for 4 years for ACL injuries, during which time 24 noncontact ACL ruptures occurred (16 in men, 8 in women). Using a hypothesis-driven logistic regression model, the factors of a narrow femoral notch, BMI 1 standard deviation or more above the mean, and generalized joint laxity explained 62.5% of the variability of the noncontact ACL tears in the female athletes. In addition, this model correctly predicted 75% (6 of 8) of the noncontact ACL injuries. The most predictive model in the men explained only 15% of the variability in the noncontact ACL injuries and was unable to predict any of the 16 injuries that occurred throughout the study period in the male athletes.

Some authors have speculated that excessive subtalar joint pronation leads to increased internal tibial rotation and resultant high forces on the ACL. Three investigations involving small sample sizes reported significantly higher navicular drop values bilaterally in patients who sustained ACL ruptures compared with matched control subjects, whereas another failed to find an association between excessive pronation and noncontact ACL injuries. A combination of postural “faults” was found to have a greater predictive value for ACL injury than a single problem (such as excessive pronation) by Loudon et al. In 20 female athletes with unilateral ACL ruptures, the combination of excessive knee hyperextension, navicular drop, and subtalar joint pronation was a strong discriminator between the patients and 20 control subjects. The authors concluded that an association existed between noncontact ACL injuries in females who had a standing posture of genu recurvatum and subtalar joint overpronation.

A few authors have reported that females appear to have greater inherent joint laxity than males. However, there is no evidence that an increase in generalized ligament laxity in females is associated with the increased risk of noncontact ACL injuries. During the last decade, the hypothesis has been advanced that fluctuations in sex hormones during certain periods of the menstrual cycle could be deleterious to the material and mechanical properties of the female ACL. The question of whether hormonal surges could have a deleterious effect on muscle and neuromuscular indices, thereby increasing the vulnerability of the ACL to rupture during certain phases of the menstrual cycle, has also been raised. A series of investigations reported that the acute hormonal fluctuations that occur during the menstrual cycle may induce changes in the metabolism of the ACL, weakening the ligament’s strength and potentially increasing its vulnerability to injury.

Three investigations that investigated 145 women who sustained ACL ruptures reported an association toward a greater proportion of female athletes suffering this injury in the preovulatory (follicular) phase compared with later phases of the cycle. Whether this observation is due to deleterious effects of hormonal fluctuations on collagen metabolism or to changes in muscle contraction and neuromuscular control remains to be determined. From these investigations, there appears to be an uneven distribution of ACL injuries in the follicular phase of the menstrual cycle; however, more data are required before definitive conclusions may be reached.

Several neuromuscular and biomechanical factors have been hypothesized to be responsible for the disparity between genders in noncontact ACL injury rates (Table 2), and this represents the area of greatest research concentration. Differences between female and male athletes in movement patterns; muscle strength, activation, and recruitment patterns; and knee joint stiffness have been demonstrated under controlled, preplanned, and reactive conditions in the laboratory. Videotape analyses of noncontact ACL injuries also demonstrate certain lower extremity positions and characteristics that lend support to the theory that these differences may likely play a role in this problem. Many noncontact ACL ruptures occur when an athlete lands from a jump in which ground reaction forces are 3 to 14 times that of the individual’s body weight. When analyzed on
videotape, noncontact ACL injuries frequently occur with a forceful valgus and tibial rotation motion, with the knee close to full extension.37

A study conducted at the authors’ laboratory using a 2-camera, video-based optoelectronic digitizer and a multi-component force plate was one of the first to demonstrate gender differences in movement patterns.48 Adolescent males demonstrated greater knee extension moments on landing and take-off, which were interpreted to be likely due to their high use of the hamstrings musculature. Males also had a greater mean hamstring/quadriceps ratio on isokinetic testing at 360° per second.

Significant differences exist between genders on the knee flexion angle measured at impact from a drop-jump49–51 and during single-leg hopping,52,53 with men consistently demonstrating greater knee flexion angles than women. Females tend to land in a more erect posture on initial impact compared with males and appear to use the ankle musculature to absorb impact forces, which is accompanied with greater knee extension and ankle plantar-flexion angles. Conversely, men demonstrate greater knee flexion and less plantar-flexion angles on impact, allowing a transfer of the forces to the larger muscles such as the hip extensors.

Chaudhari et al54 observed a correlation between frontal plane lower limb alignment and knee moments, as subjects who assumed a valgus lower limb position during a 90° lateral run-to-cut maneuver had significantly higher knee abduction moments than those who had a neutral or varus lower limb position (P < 0.01).54 Of the 21 subjects tested, 67% of females assumed a lower limb valgus alignment compared with 22% of males.

One study55 reported that female athletes had smaller knee flexion angles, greater valgus angles, increased quadriceps muscle activation, and decreased hamstring muscle activation during the stance cycle of straight running and 2 preplanned cutting maneuvers. Another investigation56 reported that during running, females had significantly greater hip internal rotation, peak hip adduction, peak knee abduction, and were in a greater abducted knee position throughout stance compared with males (Figure 1). Women have significantly greater proximal anterior shear forces, extension moments, and valgus moments on landing during stop-jump tasks compared to men57,58

| Table 2. Hypothesized Neuromuscular and Biomechanical Risk Factors for Noncontact ACL Injury in the Female Athlete |
| Category | Risk Factor | Hypothesized Gender Difference |
| Movement patterns | Knee flexion | Compared with males, females have |
| | Hip flexion | – Smaller knee and hip flexion angles during high risk activity |
| | Hip internal rotation | – Greater internal hip rotation, hip abduction, external tibial rotation, and knee abduction/adduction moments during high risk activity |
| | Hip abduction | |
| | External tibial rotation | |
| | Abduction moment | |
| | Adduction moment | |
| Muscle strength, activation, recruitment patterns | Lower extremity muscle strength and activity | Compared with males, females have |
| | Hip muscle strength | – Smaller quadriceps and hamstrings muscle torques |
| | Lower extremity muscle recruitment patterns | – Slower times to reach lower extremity muscle peak torques |
| | Fatigue | – Higher quadriceps activity and reduced hamstrings activity during athletic maneuvers |
| | Core stability | – Weaker hip muscles |
| | | – Poor core stability |
| | | – Different muscle activation patterns during preplanned and unplanned athletic tasks |
| | | – Faster time to fatigue |
| | | Females recruit hamstrings first in response to anterior tibial translation force, whereas males recruit quadriceps |
| Knee stiffness | | Compared with males, females have |
| | | – Decreased inherent passive and active knee joint stiffness |

A gender comparison of knee kinetics in 3 stop-jump tasks found that women had significantly greater proximal anterior shear forces, extension moments, and valgus moments on landing compared to men (Figure 2). The investigators believed that the increased proximal shear force was due to a high quadriceps muscle force, a low hamstrings muscle force, a straight knee on landing, or a combination of all of these factors. A second study was done to determine if gender differences existed during the preparation for landing in the vertical stop-jump task. Female recreational athletes displayed less knee and hip flexion, less hip external rotation, and increased hip abduction compared with male athletes upon preparation for landing. The authors hypothesized that the athletes “preprogrammed” these lower extremity motions during the flight phase of the last step of the approach run in this task.

Colby et al measured hamstring and quadriceps muscle activation and knee flexion angles during eccentric motion of sidestep cutting, cross-cutting, stopping, and landing in 15 collegiate athletes. A high-level quadriceps muscle activation and a low hamstring muscle activation occurred just before foot strike and peaked in mid-eccentric motion. The authors concluded that the combination of the high level of quadriceps activity, low level of hamstrings activity, and low angle of knee flexion during eccentric contractions in these maneuvers could produce significant anterior translation of the tibia. DeMorat et al reported that a high quadriceps load (4500 N) simulated in cadaveric knees at 20° of flexion produced significant anterior tibial translation (mean, 19.5 mm). These authors concluded that the quadriceps could serve as a major intrinsic force in noncontact ACL injuries.

Sell et al conducted an investigation involving high school basketball players, in which both planned and reactive
(to a visual cue) stop-jump tasks were performed vertically, horizontally to the left, and horizontally to the right. During the reactive tasks, females had lower maximum knee flexion angles than males (68.4° and 74.9°, respectively; $P = 0.001$), greater maximum knee valgus angles ($-7.5°$ and $-4.2°$, respectively; $P < 0.05$), greater anterior shear force at peak posterior ground-reaction force ($P < 0.05$), and greater knee flexion moment at peak posterior ground-reaction force ($P < 0.05$). The authors hypothesized that these differences could place greater strain on the female ACL.

Marked differences between adolescent and adult male and female athletes in quadriceps and hamstrings peak torques, even when normalized for body weight, have been documented by numerous investigations. One of the largest studies conducted to date on 853 females and 177 males aged 9 to 17 years reported that significant gender differences in lower extremity strength become evident at age 14 (Figures 3 and 4). This investigation revealed that females appear to reach peak hamstrings strength at age 11, with no significant difference found in this factor between girls 11 years of age and those up to 17 years of age.

In one study, female athletes had significantly weaker knee flexor and extensor peak torques (normalized for body weight, 60° per second and 240° per second) and endurance values than the male athletes, and were only marginally stronger than the female controls. Female athletes had slower time-to-peak torque values for knee flexors than the male athletes (430 and 328 msec, respectively; $P < 0.001$). Fatigue appears to increase the risk of ACL injury in both genders.

**Neuromuscular Retraining Programs to Decrease the Risk of Noncontact ACL Injuries**

Although many knee ligament injury prevention training programs have been published, few have presented scientific justification that the training effectively improved neuromuscular deficiencies and reduced the incidence of noncontact ACL injuries in female athletes (Table 3). Some programs had either small sample sizes or few noncontact ACL injuries and were thus underpowered to avoid the potential for a type II statistical error. Most studies were not randomized, and several did not contain a control group studied concurrently with a trained group. Although some investigations cited a reduction in noncontact ACL injury rates, others failed to find a statistically significant effect. Some programs were published even though the investigators did not follow athletes over a season or period of time to determine if a reduction in ACL injuries occurred as a result of training.

The amount of time in which an ACL rupture occurs was recently estimated to range from 17 to 50 ms after initial
The first published successful neuromuscular program, Sportsmetrics™, is a 6-week program that entails 3 training sessions per week of 60 to 90 minutes duration which has been described in detail elsewhere.8 Prior to training and immediately upon completion of the program, athletes are taken through a series of tests including single-leg hops, drop-jumps, vertical jumps, flexibility, and agility and speed tasks. The program stresses jump retraining exercises that place a major emphasis on correct body posture, form, and techniques. Specific drills and instruction are used to teach the athlete to preposition the entire body safely when accelerating or decelerating on landing (Figures 5 and 6). Next, strength training designed to focus on the development of core, hip, and lower extremity strength is performed. Based on preferences of the coach and athletes, sports-specific conditioning and agility drills may then be conducted, followed by static stretching of all major muscle groups.

This training program is effective in inducing changes in neuromuscular indices in female athletes, as studies have shown improved overall lower limb alignment on a drop-jump test,83 increased hamstrings strength,48,83,84 increased knee flexion angles on landing,48,85 and reduced deleterious abduction/adduction moments and ground reaction forces.48

A controlled prospective investigation was conducted in 1263 high school athletes to determine if Sportsmetrics™ training reduced the incidence of noncontact ACL injuries in female athletes over the course of a season.68 Three groups of soccer, volleyball, and basketball players were followed: 366 females who underwent training before the beginning of their sport season, 463 untrained females, and 434 untrained males. The total numbers of athlete exposures were 23138 for the untrained group, 17 222 for the trained group, and 21 390 for the male control group. There were 14 serious knee ligament injuries in 10 of 463 untrained female athletes (8 noncontact), 2 of 366 trained female athletes (0 noncontact), and 2 of 434 male athletes (1 noncontact). The knee injury incidence per 1000 athlete exposures was 0.43 in untrained female athletes, 0.12 in trained female athletes, and 0.09 in male athletes (\( P = 0.02 \)). Untrained female athletes had a 3.6 times higher incidence of knee injury than trained female athletes (\( P = 0.05 \)) and 4.8 times higher than male athletes (\( P = 0.03 \)). The incidence of knee injury in trained female athletes was not significantly different from that in untrained male athletes (\( P = 0.86 \)).

The second training program, which significantly reduced the incidence of noncontact ACL injuries in females, was designed specifically for soccer players.79 The prevent injury and enhance performance program (PEP) was first published in 2005 and was described as a 20-minute warm-up program available on videotape. Coaches who agreed to replace their traditional warm-up with this program implemented the training on the soccer field before practices and games. The program consists of 3 basic warm-up activities, 5 stretching exercises for the trunk and lower extremity, 3 strengthening exercises, 5 plyometric drills, and 3 soccer-specific agility activities. The videotape provides instruction, including proper biomechanical technique, for the drills and jump exercises. To date, there are no data on the effect of this training program on specific neuromuscular indices such as lower extremity muscle strength, ground reaction forces, knee abduction/adduction moments, or knee/hip flexion angles on landing.

Mandelbaum et al79 followed 1885 trained female soccer players and 3808 untrained female soccer players over the course of one season (over a 2-year period). The athletes were 14 to 18 years of age and participated in a youth soccer league. The total number of athlete exposures was 205 308. There were 73 ACL injuries that were sustained in 67 of the untrained female athletes and in 6 of the trained female athletes. The knee injury incidence per 1000 athlete exposures was 0.49 in untrained female athletes and 0.09 in trained female athletes (\( P < 0.001 \)). These authors agreed with...
### Table 3. Anterior Cruciate Ligament (ACL) Injury Prevention Training Programs

<table>
<thead>
<tr>
<th>Citation</th>
<th>Number of Athletes, Type of Sports, Number of Seasons in the Study</th>
<th>Duration of Training</th>
<th>Plyometrics</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ettlinger et al</td>
<td>4000 trained patrollers and instructors, gender unknown, 22 “ski areas” control; number not given; gender unknown Alpine skiers; 3 ski seasons</td>
<td>One hour reviewing video clips of injuries, awareness training sessions, small group discussions prevention strategies</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Caraffa et al</td>
<td>300 trained males, 300 control males; semi-professional soccer players; 3 seasons</td>
<td>20 minutes every day × 30 consecutive days preseason</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Hewett et al</td>
<td>366 trained females, 463 untrained females, 434 untrained males; soccer, basketball, volleyball; 1 season (high school)</td>
<td>1 hour 3 days/week for 6 weeks</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Wedderkopp et al</td>
<td>111 trained females, 126 untrained females; team handball; 1 10-month season</td>
<td>10–15 minutes every practice for entire season</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Heidt et al</td>
<td>42 trained females, 258 control females; soccer players, high school; 1 season</td>
<td>3 sessions/week for 7 weeks</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Myklebust et al</td>
<td>1705 trained females (855 season 1, 850 season 2); 942 control females; team handball; 3 seasons</td>
<td>15 minutes 3 times/week for 5–7 weeks, then 1 time/week during season</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Olsen et al</td>
<td>808 trained females, 778 control females, 150 trained males, 101 control males, team handball, high school; 1 season</td>
<td>15–20 minutes, average 27 sessions</td>
<td>Landing technique</td>
<td>Yes</td>
</tr>
<tr>
<td>Petersen et al</td>
<td>134 trained females, 142 control females, team handball, several divisions, adult players, 1 season</td>
<td>10 minutes, 3 times/week for 8 weeks</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Mandelbaum et al</td>
<td>1885 trained females, 3818 control females, soccer, 14–18 years of age, 2 years</td>
<td>20 minutes, replaced traditional warm-up</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Pfeiffer et al</td>
<td>577 trained females, 862 control females, soccer, basketball, volleyball high school athletes, 1 season</td>
<td>20 minutes, 2 times/week throughout season</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Steffen et al</td>
<td>1073 trained females, 947 control females; soccer; 1 season</td>
<td>15 minutes, 3 times/week for 1 season</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gilchrist et al</td>
<td>583 trained females, 852 untrained females; soccer; 1 season; collegiate players</td>
<td>20 minutes, replaced traditional warm-up</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Reducing the Risk of Noncontact ACL Injuries in the Female Athlete

<table>
<thead>
<tr>
<th>Agility</th>
<th>Balance</th>
<th>Flexibility</th>
<th>Total Number of Exposures</th>
<th>Number of ACL Injuries</th>
<th>Study Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Not given</td>
<td>179, 62% decline in serious knee ligament injuries among trained patrollers and instructors. No decline in control group.</td>
<td>Not randomized, no exposure data, no medical documentation of ACL injuries. “any mention of a grade II or III ACL sprain or grade III knee sprain included” - unknown which knee ligaments torn, unknown number of contact vs. non-contact injuries.</td>
</tr>
<tr>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Not given</td>
<td>10 in trained group, 70 in control group</td>
<td>Not randomized, no exposure data, unknown number of training sessions completed, no training of females</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>23 138 trained, 17 222 untrained, 21 390 males</td>
<td>0 trained, 5 (0.35) untrained females, 1 (0.05 males) (P = 0.05)</td>
<td>Not randomized or double-blinded, higher number volleyball players in trained group, low number of noncontact ACL injuries.</td>
</tr>
<tr>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>14 578 trained, 17 945 untrained</td>
<td>“knee sprains” 1 trained 5 untrained</td>
<td>No significant difference knee “sprains” trained vs. control group, unknown documentation method of injuries, unknown number training sessions completed.</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Not given</td>
<td>1 in trained group, 8 in control group</td>
<td>Not randomized, no exposure data, no statistically significant difference ACL injury rates trained vs. control group.</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>172 692 trained (season 1), 186 805 trained (season 2), 208 936 control</td>
<td>23 in trained season 1 (0.13), 17 injuries in trained season 2 (0.09), 29 injuries control (0.14)</td>
<td>Poor compliance with training, intervention training methods changed from 1st to 2nd season, unknown contact vs. noncontact injuries, No significant difference ACL injury rates trained vs. control group.</td>
</tr>
<tr>
<td>Planting, cutting, jumping control, awareness</td>
<td>Yes, on mats and boards</td>
<td>Yes</td>
<td>93 812 trained, 87 483 control</td>
<td>Not given</td>
<td>ACL ruptures not sorted per group, all knee ligament injuries combined.</td>
</tr>
<tr>
<td>Planting, cutting, jumping control, awareness</td>
<td>Yes</td>
<td>No</td>
<td>Not given</td>
<td>1 in trained group (0.04), 5 in control group (0.21)</td>
<td>Not randomized, no statistically significant difference ACL injury rates trained vs. control group.</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>67 860 trained, 137 447 control</td>
<td>6 in trained group (0.09), 67 in untrained group (0.49), P &lt; 0.0001</td>
<td>Not randomized, voluntary enrollment training, unknown number of training sessions completed.</td>
</tr>
<tr>
<td>Landing technique control and awareness</td>
<td>No</td>
<td>No</td>
<td>17 954 trained, 38 662 control</td>
<td>3 in trained group (0.167), 3 in control group (0.078)</td>
<td>Not randomized, no statistically significant difference ACL injury rates trained vs. control group.</td>
</tr>
<tr>
<td>Landing technique control and awareness</td>
<td>Yes</td>
<td>No</td>
<td>66 423 trained, 65 725 control</td>
<td>4 in trained group, 5 in control group</td>
<td>No statistically significant difference ACL injury rates trained vs. control group. Poor compliance completing training.</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>35 220 trained, 52 919 untrained</td>
<td>2 (0.057) trained 10 (0.189) control</td>
<td>No statistically significant difference ACL injury rates trained vs. control group, only 12 noncontact ACL injuries sustained in entire study.</td>
</tr>
</tbody>
</table>
Figure 5. The mattress jump, side-to-side is demonstrated. A cone or barrier is placed on a cushioned surface approximately 2” to 3” deep. The athlete performs a double foot jump from one side (A) over the barrier (B) to the other side (C). The feet are kept together and the athlete is instructed to begin and end the jump in the same amount of knee flexion.


others that a preventative training program should focus on developing neuromuscular control of the lower extremity through strengthening exercises, incorporate jump retraining with emphasis on proper landing technique, promote deeper hip and knee flexion during landing and lateral athletic maneuvers, teach proper deceleration techniques, and use sports-specific agility drills when appropriate.

The authors of the PEP study conducted a second investigation on female collegiate soccer athletes whose mean age was 19.8 years; 583 underwent training, and 852 served as controls. The athletes were followed during the course of one season. The total number of athlete exposures was 88,139. There were 12 noncontact ACL injuries that occurred in 2 athletes in the trained group and 10 athletes in the control group. The incidence of noncontact ACL ruptures per 1000 athlete-exposures was 0.189 in untrained female athletes and 0.057 in trained female athletes ($P = 0.066$). The study lacked the statistical power to compare subgroups because of the smaller than expected number of noncontact ACL injuries reported.

Conclusions

The increased incidence of knee ligament injuries in female athletes is multifactorial, and it is currently unknown which factors are dominant and which play a smaller role. A number of intrinsic factors inherent in women have been suggested, including a narrow intercondylar notch, smaller-sized ACL, pelvic-hip-knee-foot alignment, generalized knee laxity, foot pronation, and hormonal fluctuations. Extrinsic factors related to athletic conditioning, skill, training, and equipment have also been discussed. Although issues related to differences in neuromuscular control, muscle reaction patterns, coordination and control of body and lower-extremity positions during athletics are usually related to extrinsic factors, it may be that these factors are both intrinsic and extrinsic in their development.

In order to determine which risk factors for noncontact ACL ruptures are significant and which may play a more negligible role, future investigations must include greater sample sizes, analyze factors from all of the major categories (anatomical, environmental, hormonal, and neuromuscular), and follow athletes for at least one entire athletic season for injury. Athletes from multiple sports should be included to determine if certain factors are sports specific in terms of injury risk. Future studies need to incorporate reactive tasks, as there appear to be significant differences in movement and muscle activation patterns under these conditions versus those of controlled preplanned maneuvers. As technology
improves, these studies may hopefully be able to move out of the laboratory and measure neuromuscular indices under actual playing conditions.

Few neuromuscular retraining programs have significantly (and with adequate statistical power) reduced the incidence of noncontact ACL ruptures in female athletes. The 2 published successful programs implement specific teaching techniques designed to alter movement patterns and strength in the core and lower extremity. Future studies need to include larger number of athlete exposures either over the course of a single season or over multiple seasons in order to have sufficient power to avoid the potential for a type II statistical error.

Conflict of Interest Statement
Sue D. Barber-Westin, BS, Frank R. Noyes, MD, Stephanie Tutalo Smith, MS, Thomas M. Campbell, BA disclose no conflicts of interest.

References


