American Journal of Sports Medicine

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Am. J. Sports Med. 2006; 34; 1512
DOI: 10.1177/0363546506286866

The online version of this article can be found at:
http://ajs.sagepub.com/cgi/content/abstract/34/9/1512

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On behalf of:

American Orthopaedic Society for Sports Medicine

Understanding and Preventing Noncontact Anterior Cruciate Ligament Injuries

A Review of the Hunt Valley II Meeting, January 2005

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The American Journal of Sports Medicine, Vol. 34, No. 9
DOI: 10.1177/0363546506286866

†Although all authors contributed to the intellectual material in the article and made some direct contribution to the actual writing and review of the text, these authors made a major contribution to text development. The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the United States Government.

One or more of the authors has declared a potential conflict of interest: The AOSSM provided research funds to study jump landing in midshipmen at USNA. However, no authors personally received any funds for research.

The incidence of noncontact anterior cruciate ligament injuries in young to middle-aged athletes remains high. Despite early diagnosis and appropriate operative and nonoperative treatments, posttraumatic degenerative arthritis may develop. In a meeting in Atlanta, Georgia (January 2005), sponsored by the American Orthopaedic Society for Sports Medicine, a group of physicians, physical therapists, athletic trainers, biomechanists, epidemiologists, and other scientists interested in this area of research met to review current knowledge on risk factors associated with noncontact anterior cruciate ligament injuries, anterior cruciate ligament injury biomechanics, and existing anterior cruciate ligament prevention programs. This article reports on the presentations, discussions, and recommendations of this group.

Keywords: anterior cruciate ligament (ACL) injuries; injury prevention; athletic injuries; knee injuries

As stated by Flynn et al,[49] "Rupture of the ACL of the knee is a serious, common, and costly injury." Each year, an estimated 80 000 to more than 250 000 ACL injuries occur, many in young athletes 15 to 25 years of age. In fact, this group of young athletes composes more than 50% of all those sustaining ACL injury.[43,54,56,70] Anterior cruciate ligament reconstruction is a commonly performed procedure. Data collected by the American Board of Orthopaedic Surgeons for part II of the Certification Examination reveal that in 2004, ACL reconstruction ranked sixth among the most common surgical procedures performed by all sports medicine fellows and third among those surgeons identified as generalists.[52] The Centers for Disease Control and Prevention has reported that about 100 000 ACL reconstructions are performed annually.[26]

The consequences of ACL injury include both temporary and permanent disability with the resultant direct and indirect costs. Subsequent to ACL injury, there may be loss of time from work, school, or sports. The natural history of ACL tears and the long-term consequences of the injury, whether surgically reconstructed or not, remain under debate. Several retrospective studies have identified the development of posttraumatic degenerative joint disease in knees after ACL injury despite surgical reconstruction.[‡] Therefore, it is not sufficient to emphasize only prompt recognition and appropriate treatment algorithms, but orthopaedic surgeons must develop prevention strategies and verify them using scientific methods. Implicit to the development of injury prevention programs is the identification of athletes at increased risk for noncontact ACL injury.

In Hunt Valley, Maryland, in 1999, a group of physicians, physical therapists, athletic trainers, and biomechanists interested and engaged in this area of research met to review and summarize data on risk factors for injury, injury biomechanics, and injury prevention programs. The group also identified ideas for further research (Table 1).[61,62]

Since 1999, many additional studies exploring risk factors for ACL injury, injury biomechanics, and injury prevention program development have been published. Furthermore, studies have tried to identify the significant components of effective prevention programs as well as the impact these programs have on what is known regarding injury risk factors and biomechanics. With this new wealth of material, those who attended the first Hunt Valley meeting felt that a second Hunt Valley meeting was warranted to review and discuss these new developments. Such a meeting was held in Atlanta, Georgia, in January 2005.

This article is a summary of the panel's presentations, discussions, and recommendations.

RISK FACTORS ASSOCIATED WITH NONCONTACT ACL INJURY

Two different classification schemes have been used when discussing risk factors for noncontact ACL injury. In the first, risk factors are divided into extrinsic factors (those outside the body) and intrinsic factors (those from within the body).[115] The second scheme divides risk factors into the following 4 categories: environmental, anatomical, hormonal, and neuromuscular. Because this latter scheme for risk factor classification was used for both the Hunt Valley I and Hunt Valley II meetings, the authors elected to use it for the basis of this article. Familial tendency to injury has also been reported and is included as a fifth category in this discussion.

Environmental Risk Factors

Environmental (external) factors include meteorological conditions, the type of surface (grass, hard floor, etc), the type of footwear and its interaction with the playing surface, and protective equipment such as knee braces.

Meteorological Conditions. In a prospective study of Australian football, Orchard et al[129] reported that noncontact ACL injuries were more frequent during high-evaporation and low-rainfall periods. The harder ground conditions during these climatic conditions presumably increase the shoe-surface traction and the risk of ACL injury. However, confounding by other factors cannot be eliminated, and there is a need for randomized controlled trials of interventions such as ground watering during dry periods.[128,129]

Surfacing. A prospective cohort study of 8 high school football teams in Texas noted an approximately 50% reduction in the rate of ACL injury on the latest generation of artificial turf ("FieldTurf"), relative to natural grass. This study recorded only 14 ACL injuries and did not include data on type of footwear worn or the traction of the surface.[107] A retrospective analysis of 53 ACL injuries in Norwegian team handball (based on data collected in previous studies) found an increased risk of ACL injury on artificial floors, relative to natural wood floors, in women (odds ratio, 2.4; 95% confidence interval, 1.1-5.1) but not in men.[127] Friction tests documented a higher coefficient of

‡References 35, 44, 46, 93, 117, 136, 137, 153, 161.

TABLE 1
Consensus Statement: 1999 Hunt Valley I Meeting

Environmental risk factors
• No evidence exists that knee braces prevent ACL injuries.
• Increasing the shoe-surface coefficient of friction may improve performance but also may increase the risk of injury to the ACL. Because shoe-surface interaction is modifiable, this area merits further investigation.
Anatomical risk factors
• There is much literature on the relation of femoral notch size to ACL injury, but because of the difficulty in achieving valid and reliable measurements, no consensus on the role of the notch in ACL injury can be reached at this time.
• Data on ACL size (absolute or proportional) are insufficient to determine whether ligament size is related to the risk of injury.
• Insufficient data exist to relate lower extremity anatomical alignment to ACL injury, but further research is needed.
Hormonal risk factors
• No consensus exists in the scientific community that sex-specific hormones play a role in the higher incidence of ACL injury in female athletes, but further research in this area is encouraged.
• Hormonal intervention for ACL injury prevention cannot currently be justified.
• No evidence exists to recommend modification of activity or restriction from sports participation for women at any time during their menstrual cycles.
Biomechanical risk factors
• The knee is one part of a kinetic chain, and anatomical sites other than the knee, including the trunk, hip, and ankle, may contribute to ACL injury.
• Biomechanical factors involved with many (but not all) ACL injuries include impact on the foot rather than on the toes during landing or changing directions, awkward dynamic body movements, and perturbation before the injury.
• The most common high-risk situation for noncontact ACL injuries appears to be deceleration, which occurs when the athlete cuts or changes direction or lands from a jump.
• Neuromuscular factors appear to be the most important reason for the different ACL injury rates in men and women.
• Strong quadriceps activation during eccentric contraction was felt to be a major factor in injury to the ACL.
Prevention strategies
• Early data show that specific training programs that enhance body control reduce ACL injury rates in female athletes and may increase athletic performance.
• Training and conditioning programs may need to be different for male and female athletes in the same sport.
• Those involved in the care of athletes should identify sport-specific high-risk motions and positions and encourage athletes to avoid these situations when possible.
• Strategies for activating protective neuromuscular responses when high-risk situations are encountered should be identified.

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friction in the artificial floors, suggesting that the shoe-surface traction on these floors would be increased. Greater traction may interact with intrinsic risk factor(s) (presumed to be more prevalent in women than in men) to increase the risk of ACL injury.[127]

Footwear. Earlier studies suggested that shorter cleat length was associated with a reduced risk of knee and ankle injuries.[86,135] However, in recent years, there has been limited laboratory or epidemiologic research addressing footwear and its interaction with the type of playing surface, possibly because of the complexity of this relationship, which may be further modified by intrinsic factors. It is quite plausible that increased shoe-surface traction is a direct risk factor for ACL injury, but it should also be noted that athletes modify their movement patterns to adapt to variations in shoe and surface factors and thereby may alter neuromuscular and biomechanical factors that influence ACL injury risk.[108] Thus, the shoe-surface interaction may affect ACL injury risk directly (through higher traction) and indirectly (because higher traction may alter human movement factors that influence ACL injury risk).

Knee Braces. The use of prophylactic knee braces to prevent knee injuries has long been a contentious area of research. The best study to date of prophylactic knee braces and ACL injury remains a randomized prospective study of 1396 cadets playing intramural tackle football at the US Military Academy. This study found that prophylactic knee brace use was associated with a reduced rate of knee injury.[148] Based on the data published in this article, we compute that the rate of ACL injury in the nonbraced cadets was 3.0 times higher (95% confidence interval, 1.0-9.2) than in braced cadets. It should be noted that the number of ACL injuries was small (only 16, with 4 in braced and 12 in the nonbraced). The other large epidemiologic study conducted to date also focused on football but did not examine ACL injury.[2] The biomechanical evidence on the effect of prophylactic knee braces on the ACL remains equivocal.[121]

Functional knee braces can reduce the AP laxity of the ACL-deficient knee to within the limits of the normal knee during nonweightbearing or weightbearing activities. However, in the ACL-deficient knee, braces do not reduce the abnormal increased anterior displacement of the tibia relative to the femur as the knee transitions from nonweightbearing to weightbearing conditions.[16,17] A controlled laboratory study on a new functional knee brace with a constraint to knee extensions found that the new knee brace significantly increased knee flexion angle in a stop-jump task.[171]

A prospective study of 180 skiers with ACL deficiency identified from screening 9410 professional skiers reported a higher risk of knee injury in skiers who did not wear a functional knee brace compared with those who wore a functional knee brace (risk ratio of 6.4, based on a total of 12 injuries).[85] A prospective, randomized, multicenter study examined 100 cadets at the 3 largest US military academies who underwent ACL reconstruction and were randomized to either functional brace use or no brace use. At 1 year after surgery, the use of a functional brace appeared to have no effect on the incidence of graft tear; however, there were only 5 reinjuries (2 in the braced and 3 in the nonbraced).[100]

Summary of Environmental Factors. The evidence regarding environmental factors is confusing and mixed. The few methodologically rigorous studies that have been performed are limited by small numbers of ACL injuries. It seems plausible that harder surfaces and shoes with longer cleats increase shoe-surface traction and the risk of ACL injury, but definite evidence of effects has not been obtained to date. The biomechanical and epidemiologic literature on brace use (prophylactic and functional) is equivocal and inconsistent. In general, there is a need for studies addressing environmental risk factors that better integrate biomechanical and epidemiologic knowledge. Such studies would also ideally consider the interaction of extrinsic and intrinsic factors.

Anatomical Risk Factors

The mechanical alignment of the lower extremity contributes to the overall stability of the athlete's knee joint. The magnitude of the quadriceps femoris angle (Q angle), the degree of static and dynamic knee valgus, foot pronation, body mass index (BMI), the width of the femoral notch, and ACL geometry are anatomical factors that have been associated with an increased risk for noncontact ACL injury.

Q Angle. The Q angle has been proposed as a contributing factor to the development of knee injuries by altering lower extremity kinematics.[67,110] Studies have consistently observed larger Q angles in young adult women compared with young adult men.[76,79,92,112]

Shambaugh et al[140] investigated the relationship between lower extremity alignment and injury in recreational basketball players. They studied 45 athletes, taking various structural measurements, and found that the mean Q angles of athletes sustaining knee injuries were significantly larger than the mean Q angles for the players who were not injured (14° vs 10°).

The degree of Q angle can also have interdependent effects on other key ACL risk factors. In 2003, Buchanan[24] performed a case-control study of 50 healthy, prepubescent, peripubescent, and postpubescent female and male basketball players (aged 9-22 years) not only to assess valgus-varus knee position during single-leg landings but also to asses whether gender, age, years of informal and formal basketball experience, Q angle, and strength could predict the valgus-varus knee position on landing. Buchanan[24] found that prepubescent female and male players had mostly valgus knee positions on landing. Among peripubescent and postpubescent groups, female players continued to have mostly valgus knee positions, whereas male players had mainly varus knee positions. The static Q angle (along with ankle strength) predicted 32.4% to 46% of the variance in valgus-varus knee position.[24]

Knee Valgus. A common factor in noncontact ACL ruptures may be the position of the lower extremity during the injury. The valgus position of the lower extremity has long been viewed as hazardous for the ACL, based on clinical observations,[97] biomechanical studies,[§] and systematic video analysis.[125]

Recent work by Ford et al[50] used 3D motion analysis to determine whether gender differences existed in knee valgus kinematics in 81 high school basketball athletes (47 female, 34 male). Valgus knee motion and varus-valgus angles were calculated while subjects performed a vertical jump-landing maneuver. They found that the female subjects landed with significantly greater total valgus knee motion and greater maximum valgus knee angle than did the male subjects.

In a subsequent study, Hewett et al[72,73] prospectively followed 205 female athletes participating in the high-risk sports of soccer, basketball, and volleyball and measured 3D kinematics and joint kinetics during a jump-landing task. These investigators found that the dynamic knee valgus measures were predictive of future ACL injury risk ($r^2 = 0.88$).

Foot Pronation. Research suggests that excessive pronation of the foot may contribute to the incidence of ACL tears by increasing internal tibial rotation.[3,21,94,151,170] Studies have documented greater navicular drop values in individuals with a history of an ACL tear using methods that accurately follow the motion of underlying bone.[3] However, controversy exists as to whether this structural variable is a significant predictor for ACL injury.[3,151]

For example, Allen and Glasoe[3] compared the navicular drop of subjects with a history of ACL tears with that of healthy controls when measured by a Metrecom system. Eighteen subjects who were previously diagnosed with a torn ACL were matched by age, sex, and limb to noninjured control subjects. A single investigator performed the measure of navicular drop using a digitizing protocol that assessed the difference between the amount of navicular drop in the ACL group and the controls. They concluded that excessive subtalar joint pronation, measured as navicular drop, may contribute to ACL injury.

Woodford-Rogers et al[170] used a case-control series, identifying 14 ACL-injured football players and 8 ACL-injured female basketball players and gymnasts and matching them with 22 athletes (without a history of ACL injury) by sport, team, position, and level of competition. Measures of navicular drop, calcaneal alignment, and anterior knee joint laxity using a KT-1000 arthrometer were obtained from the uninjured knee of the ACL-injured athletes and compared with measures obtained from the noninjured athletes. Athletes with ACL injuries were found to have greater degrees of navicular drop, suggesting a greater subtalar pronation and greater anterior knee joint laxity. These results suggest that the more an athlete pronates (as well as the greater the knee joint laxity), the greater the association with ACL injury.

[§]References 13, 14, 18, 20, 41, 50, 73, 99, 102, 103.

Loudon et al[94] also examined the correlation between static postural faults in female athletes and the prevalence of noncontact ACL injury. They evaluated 20 female athletes with ACL injuries and 20 age-matched controls and measured several variables: standing pelvic position, hip position, standing sagittal knee position, standing frontal knee position, hamstring length, prone subtalar joint position, and navicular drop test. They concluded that knee recurvatum, an excessive navicular drop, and excessive subtalar joint pronation were significant discriminators between the ACL-injured and the noninjured groups.

Conversely, Smith et al[151] were unable to predict injury risk by using the navicular drop score and concluded that hyperpronation, as measured by the navicular drop test, may not be a predisposing factor to noncontact ACL injury.

Body Mass Index. A recent prospective cohort study in cadets at the US Military Academy found that in women, a higher than average BMI was associated with an increased injury risk.[159]

In a cross-sectional study of college-aged recreational athletes, Brown et al[23] added support for increased BMI as a risk factor for ACL injury. They found that an increase in BMI resulted in a more extended lower extremity position with decreased knee flexion velocity on landing, factors that may favor ACL injury. However, Knapik et al[84] in a prospective study of risk factors associated with training-related injuries among men and women in basic combat training did not find BMI associated with an increased risk of injury in female military recruits, nor did Ostenberg and Roos[130] find a positive correlation between BMI and injury in female soccer players. Hence, the data on BMI appear to be inconsistent, making it difficult to draw reliable conclusions.

Notch Size, ACL Geometry, and ACL Material Properties. In general, geometric differences in the size and shape of the ACL have not been well characterized. In addition, studies reporting on the ACL geometry and on notch dimensions are difficult to interpret because of the lack of standardized methods to obtain the data. However, it is generally accepted that the stresses in a smaller ACL will be greater for a given applied load. In addition, the load at failure will be lower in an ACL with a smaller area if the material properties of the ACL are equal between the samples. Under these circumstances, a sex difference in the size, shape, or structure would be an important finding partially explaining the sex difference in ACL injury.

Arendt[7] summarized the existing data on notch width and the relationship of this anatomical factor to injury, noting that notch width (regardless of measurement technique) of bilateral ACL-injured knees is smaller than that of unilateral ACL-injured knees and that notch width of bilateral and unilateral ACL-injured knees is smaller than notch width of normal controls, implying an association between notch width and injury.

In a prospective study of 902 high school athletes, Souryal and Freeman[154] concluded that athletes with a small intercondylar notch as measured radiographically on a standard notch view had an increased risk for noncontact ACL injury. LaPrade and Burnett,[89] also using a prospective study design in a cohort of 213 collegiate athletes, concluded similarly that athletes with a narrow intercondylar notch width as measured radiographically on a standard notch view are at an increased risk for noncontact ACL injury. Others have concurred with their results.[5,66,95,141,159]

However, a number of studies in the literature have reported no correlation between notch width and the incidence of noncontact ACL injuries but do not have sufficient power to make definitive conclusions. Schickendantz and Weiker[138] in a retrospective study using a variety of different mathematical measurements on notch radiographs in 30 unilaterally injured knees, 31 bilaterally injured knees, and 30 controls found no significant difference. In another retrospective study comparing notch size as measured on a notch radiographic view between 40 normal knees and 40 knees in patients who sustained a noncontact ACL injury, Teitz et al[157] found no significant difference in notch sizes between injured and uninjured knees, and Anderson et al[4] in a prospective study employing 100 high school basketball players (50 male and 50 female) found no statistically significant difference in the notch width index between male and female players.

Anterior cruciate ligament size as a risk factor for ACL injury continues to be evaluated. Methods to determine notch size and ACL size vary from radiographic, MRI, and photographic techniques. Measurements are made in 1 or multiple dimensions by contact (calipers) or noncontact (digital or laser) methods. Each technique has its inherent strength and weakness. For example, contact methods usually require cadaveric specimens and underestimate the size because of the contact of the caliper to the ligament. Noncontact methods can be used on cadaveric tissue or patient tissue using imaging techniques that do not touch the ACL but may require extrapolation of size near the ACL attachment sites. Anderson et al,[4] using MRI measurements of the ACL area at the notch outlet, found in a prospective study of high school basketball players that ACLs in girls were smaller than in boys when normalized for body weight. A positive correlation between small ACLs and injury risk was found by Shelbourne and Kerr[142] and Uhorchak et al.[159] In a descriptive anatomical study, Charlton et al,[32] using MRI, found that the volume of the ACL in the femoral notch midsubstance was smaller in women compared with men and that this difference was related to height. In addition, they found subjects with smaller notches also had smaller ACLs. Chandrashekar et al,[29] in a descriptive cadaveric study, found the ACL in women was smaller in length, cross-sectional area, volume, and mass when compared with that of men. However, no differences were found in notch geometry between men and women. However, in men (but not women), larger notches were highly correlated to have ACLs with larger masses. Muneta et al,[114] in a study of cadaveric embalmed Japanese knees relating notch width with direct caliper measurements and ACL size by rubber mold measurements, concluded that in the 16 cadaveric knees studied, knees with smaller notches did not have smaller ACLs.

Chandrashekar et al,[28] in an abstract presented at the 29th annual meeting of the American Society of Biomechanics, reported that compared with a male ACL, the female ACL has a lower mechanical quality (8.3% lower strain at failure, 14.3% lower stress at failure, 9.43% lower strain energy density at failure, and, most important, 22.49% lower modulus of elasticity) when considering ACL and body anthropometric measurements as covariates. The abstract has not been published in paper form but deserves mention because it brings forth the possibility that male and female ACLs have different material properties. This needs further study at both the gross and molecular levels.

A high level of evidence supports the idea that decreased notch width is associated with increased ACL injury risk. Recent reports have concluded that ACLs of females are probably geometrically smaller than those of males when normalized by BMI. The ACL material properties may possibly be different between the sexes and need further study. Even if an association between notch width and noncontact ACL injury risk is reliably found, the mechanism by which notch width might be related to ACL injury remains speculative. Finally, although it appears that ACLs of women are smaller than those of similar-sized men, it is unknown if the intersegmental (between femur and tibia) load applied to a smaller ACL is actually high enough to cause ACL injury.

Summary. Anatomical risk factors remain an intriguing area of research. However, to date, conflicting data exist in a variety of study designs regarding the magnitude of the Q angle, the degree of static and dynamic knee valgus, foot pronation, BMI, the width of the femoral notch, and ACL geometry as risk factors for ACL injury. Although exploring anatomical risk factors improves our understanding of the ACL risk factor equation, one must appreciate that if anatomical factors are found to be definitely associated with an increased risk of injury, they may be more difficult to modify than are environmental, hormonal, or neuromuscular factors.

Hormonal Risk Factors

Sex hormones have been shown to play a role in the regulation of collagen synthesis and degradation in studies of human ligament tissue in vitro[173] and in studies of rat connective tissue using both in vitro[40] and in vivo[1,45,64,143] models. Increased interest in sex hormones as a risk factor for noncontact ACL injury followed Liu and Sciore's discovery of receptors for these hormones in ACL tissue obtained from male and female subjects.[91] Because hormones are known to affect the properties of ligament loading and because of the higher incidence of ACL tears in women, a number of studies have been conducted to evaluate the role of sex hormones in ACL injury.[149] These experiments involve laboratory studies in cell culture, animal studies, and human studies comparing men and women, as well as women across different phases of their menstrual cycles.

Hormones and Animal ACL Tissue. Cell culture and biomechanical studies have evaluated the effect of estrogen on the ACL in several animal models, including sheep, goats, and rabbits, and have yielded conflicting results. Using a prospective, matched-control design, Slauterbeck et al[149] demonstrated a lower load to failure of the ACL in ovariectomized rabbits after 30 days of treatment with estradiol (concentrations consistent with pregnancy level) compared to controls. Using cell culture methods, Seneviratne et al[139] prospectively examined sheep ACL fibroblasts that were subjected to different physiologic doses of estradiol and found no difference in fibroblast proliferation and collagen synthesis. In another controlled laboratory study, Strickland et al[155] found no difference in the biomechanical properties in sheep knee ligaments at 6 months after random assignment to sham-operated, ovariectomy, ovariectomy and estradiol implant, low-dose raloxifene (estrogen agonist), and high-dose raloxifene groups. The relevance of these studies to humans, however, is uncertain, as only humans and the great apes (chimpanzees, gorillas, and orangutans) have menstrual cycles. All other mammals have estrous cycles. Because of this difference, the panel recommends use of human ACL tissue to study sex and hormone effects.

Hormones and Human ACL Tissue. Cells harvested from human ACL tissue have been studied after being subjected to increasing concentrations of estrogen and progesterone. Yu et al[173,174] prospectively evaluated the effects of both physiologic and supraphysiologic levels of 17β-estradiol and progesterone on cell proliferation and collagen synthesis in human ACL fibroblast cell cultures. The results of these in vitro studies indicated a dose-dependent decrease in fibroblast proliferation and type 1 procollagen synthesis with increasing levels of estradiol that eventually plateaued at supraphysiologic levels. This inhibitory effect was attenuated with increasing concentrations of progesterone. In fact, when estradiol levels were controlled, they observed a dose-dependent increase in fibroblast proliferation and type 1 procollagen synthesis with increasing levels of progesterone. The hormonal effects observed were most pronounced in the initial days after hormone exposure (days 1 and 3) and began to attenuate within 7 days of exposure. Collectively, these results suggest that acute increases in sex hormone concentrations across the menstrual cycle may influence ACL metabolism and collagen synthesis in an interactive, dose-dependent, and time-dependent manner.

Hormones and Knee Laxity. Results of animal and human tissue studies have led others to examine how changes in sex hormones across the menstrual cycle affect knee laxity in normal-menstruating women. Many studies investigating this relationship have been limited in study design because of small sample sizes, limiting testing to a specific day or days of the menstrual cycle, lack of hormone confirmation to define cycle phase, lack of comparison between sexes, and inconsistent definition of the phase of the menstrual cycle.

Using a standard knee arthrometer and standard anteriorly directed loads of 89 N and 134 N, researchers have found significant increases in AP knee laxity during the periovulatory and luteal phases compared with menses (ie, the early follicular phase).[37,69,146] Other prospective cohort studies did not detect variable laxity with the phase of the menstrual cycle.[15,81,160] However, these latter studies either did not measure hormone concentrations to confirm the actual phase of the cycle[81] or limited their testing to a single test day to represent a particular phase of the menstrual cycle for each female subject.[15,160] Because hormone profiles (eg, cycle length, hormone phasing, and hormone concentration changes) vary considerably between normal-menstruating females,[88] using serum or urine hormone concentrations to document and define cycle phase rather than using an identified day or range of days of the menstrual cycle is essential. Furthermore, the inherent variability in the timing of hormone changes between women also creates challenges for group comparison studies when attempting to identify a time point in the cycle that represents the same hormonal milieu for all women.

To address some of these limitations, Shultz et al[146] comprehensively examined the relationship between sex, sex hormones, and knee laxity in a controlled prospective cohort study of men and women. The KT-1000 arthrometer measurements and serum sex hormone concentrations were obtained daily for women through 1 complete menstrual cycle and were compared with men who were measured once per week for 4 weeks. Sex differences in knee laxity were cycle dependent (phases defined by serum hormone levels), with knee laxity differences being greatest in the early luteal phase of the menstrual cycle. Sex hormones explained, on average, approximately 68% of the change in knee laxity within each female subject across her menstrual cycle when a time delay (ie, a time lag from when hormone concentrations changed to when knee laxity changed) was taken into consideration.[145] However, it is important to note that not all women experience cyclic increases in knee laxity. Further analysis of these data suggests that minimum estradiol and progesterone levels during menses in part mediate this response.[144] The implications of these cyclic increases in knee laxity on knee joint biomechanics and ACL injury risk have yet to be determined.

Anterior Knee Laxity and ACL Injury Risk. The implications of greater absolute and cyclic increases in anterior knee laxity on ACL injury risk are relatively unknown. Although anterior knee laxity is frequently cited as a potential risk factor, we found only 2 risk factor studies that have included anterior knee laxity as a variable. As previously mentioned, in a retrospective, matched-control study of male football players and female basketball players and gymnasts (n = 22 per group), Woodford-Rogers et al[170] compared the noninjured lower extremity of the ACL-injured subjects with uninjured controls on navicular drop, calcaneal alignment, and anterior knee joint laxity and found greater measures of navicular drop and anterior knee laxity in the injured athletes. In a prospective cohort study of 1200 military cadets, a total of 24 noncontact ACL injuries were documented. Anterior knee laxity values that exceeded 1 SD or more above the mean, along with femoral notch width, generalized joint laxity, and higher than normal BMI, explained 28% of the variance in noncontact ACL injuries.[159] Women with knee laxity values greater than 1 SD of the mean had a 2.7 times higher relative risk of injury than did women with lower knee laxity values. Anterior knee laxity was not a predictor of injury in men. Although these studies implicate anterior knee laxity as a potential ACL injury risk factor, they are limited to relatively small samples of ACL-injured subjects, and much larger samples are needed to achieve adequate statistical power to examine a full complement of ACL injury risk factors.[159] Furthermore, only 20% to 30% of the variance in injury group classification was explained by anterior knee laxity (in combination with other variables), indicating there is still a substantial amount of variance in injury risk that is not explained by these factors. The implications of cyclic increases in anterior knee laxity on ACL injury risk have yet to be explored.

Menstrual Cycle Phase and ACL Injury. The relationship between the phase of the menstrual cycle and the incidence of noncontact ACL injury remains unclear. A variety of study designs (case series, case control, retrospective, prospective, and surveys) have been used to examine this risk factor. Greater than expected numbers of noncontact ACL injuries have been found during both perimenstrual[120,150] and preovulatory[167] days of the cycle. Two other studies generally identified the follicular (preovulatory) phase as being a higher risk phase of the cycle than is the luteal phase for noncontact ACL injury.[8,19]

Only 3 studies[19,150,167] have measured actual hormone levels to confirm cycle phase at the time of injury. Using a case series study design, Wojtys et al[167] measured urine hormone levels in 69 women at the time of injury and identified more injuries around the ovulatory phase (high estrogen levels) and before the rise of progesterone in those women not on oral contraceptives. Using a similar approach, Slauterbeck et al[150] used questionnaires and saliva samples within 72 hours of injury to document cycle phase and identified a higher frequency of ACL injury in the days immediately before and after the onset of menses in a cohort of 38 women with ACL injuries. Most recently, Beynnon et al[19] examined the likelihood of suffering an ACL injury by cycle phase in a case control study of 91 alpine skiers (46 injured, 45 uninjured). The menstrual cycle was divided into preovulatory and postovulatory phases based on serum progesterone concentrations obtained at the time of injury. They determined that the odds of suffering an ACL injury were significantly elevated in the preovulatory phase compared with the postovulatory phase of the menstrual cycle (odds ratio, 3.22), with 74% of the injured subjects being in the preovulatory phase, whereas only 56% of the controls were in the preovulatory phase.

Although there is no clear consensus in the literature or by the Hunt Valley II panel as to the hormonal level or the specific time in the menstrual cycle in which noncontact ACL injury is more likely to occur, studies defining cycle phase, based on actual hormone concentrations, appear to be consistent in that no study has yet to identify a greater risk of injury in the luteal phase of the cycle. Prospective, controlled studies are required to clarify the relationship between cycle phase and noncontact ACL injury. Based on the time-dependent effects of sex hormones on collagen metabolism[173] and knee laxity,[145] documentation of actual hormone concentrations in the days preceding the injury (not just the day of injury) may be important to accurately characterize the hormone milieu leading up to the injury event.

Summary. Much remains unknown regarding the effects of sex hormones on ACL structure and injury risk. Although mounting evidence suggests that sex hormones mediate cyclic increases in knee laxity across the cycle, further research is needed to determine the implications of these cyclic increases on knee joint stability and injury risk. Furthermore, universal agreement has not been reached concerning the time in the menstrual cycle at which the greatest number of injuries occur. Although the evidence is not conclusive, the preponderance of evidence would indicate more injuries occur in early and late follicular phases. Future research should consider and appreciate the inherent individual variability in cycle characteristics between women and accurately document each woman's hormone milieu with actual hormone concentrations.

Neuromuscular Risk Factors

Neuromuscular risk factors continue to evolve, and their elucidation is intertwined with a greater understanding of the mechanics of injury. Many publications addressing neuromuscular risk factors are controlled laboratory studies. Although these studies provide strong theoretical support to clinical observations, further studies are still needed to establish the association between the injury and proposed neuromuscular risk factors. The proposed neuromuscular risk factors may be grouped as those related to altered movement patterns, altered activation patterns, and inadequate muscle stiffness.

Altered Movement Patterns. Controlled laboratory studies have repeatedly shown that women, compared with men, appear to land a jump, cut, and pivot with less knee and hip flexion, increased knee valgus, increased internal rotation of the hip, increased external rotation of the tibia, less knee joint stiffness, and high quadriceps activity relative to hamstring activity, that is, quadriceps-dominant contraction.[‖] Those interviewed have reported knee hyperextension at the time of injury, but videos have not verified this position. Aggressive quadriceps loading of the knee has been found in cadaveric studies to result in significant anterior translation of the tibia relative to the femur, and hence it has been proposed as a potential mechanism of injury.[39] This finding is consistent with work by Wascher et al,[162] who used a cadaveric model in a series of controlled loading experiments to measure the resultant forces exerted by the ACL and PCL on their respective femoral and tibial insertions. Other controlled laboratory studies reported that women have "leg dominance," that is, an imbalance between muscular strength, flexibility, and coordination between their lower extremities, and such imbalances are associated with an increased risk of injury.[12,50,73,83,116]

In another laboratory controlled study, Yu et al[172] found that boys and girls have similar knee flexion angles at ground contact before the age of 12 years, and girls have decreased knee flexion angles after age 13 years. Hewett et al theorized that unlike boys, girls do not have a neuromuscular spurt to match their growth spurts. Moreover, their rapid increase in size and weight at about or near the time of puberty, in the absence of increased neuromuscular power and neuromuscular control, may increase the risk of ACL injury.[72]

Fatigue appears to be a factor that has negative effects on dynamic muscle control of the lower extremity and hence, perhaps, an association with injury. In a controlled laboratory study, Chappell et al[30] found that male and female recreational athletes had a decrease in knee flexion angle and increase in proximal tibial anterior shear force and knee varus moment when performing stop-jump tasks with lower extremity fatigue. Theoretically, these changes in movement patterns due to fatigue tend to increase ACL loading.

Altered Muscle Activation Patterns. Quadriceps-dominant contraction occurring during landing and cutting activities has been reported to be an important risk factor in several controlled laboratory studies.[¶] These studies demonstrated lower levels of hamstring activity compared with quadriceps activity during landing and cutting. The high level of quadriceps activity and low level of hamstring activity, especially during an eccentric contraction, may produce significant anterior displacement of the tibia. At least 3 well-designed controlled laboratory studies showed that female athletes had muscle activation patterns in which the quadriceps predominated and decreased knee stiffness occurred. Huston and Wojtys[78] found quadriceps-dominant muscle-stabilizing responses to anterior tibial translation compared with male and female nonathlete controls. Malinzak et al[97] reported that female recreational athletes had greater quadriceps muscle activation and lower hamstring activation than did their male counterparts. White et al[165] found quadriceps coactivation ratios significantly higher in collegiate female athletes compared with their male counterparts.

Inadequate Muscle Stiffness. Four controlled laboratory studies comparing knee stiffness in noninjured healthy male and female subjects measured significantly decreased stiffness in the female cohort.[57,58,82,166,168] Kibler and Livingston[82] measured longer activation duration on muscles that initiated and maintained knee (gastrocnemius) and lower extremity stiffness (gluteus) in male college athletes compared with female college athletes. The consequences of this may lead to increased anterior tibial translation and decreased knee stiffness. Granata et al[57,58] measured the transient motion to an angular perturbation in male and female subjects. Significantly less effective muscle stiffness in the quadriceps and hamstrings occurred in the female subjects. Wojtys et al[166] conducted 2 different studies in men and women. The percentage increase in shear knee stiffness in response to an anteriorly directed perturbation of the knee in men was much greater (379%) than that in women (212%). In the other study, male and female cohorts were matched for height, weight, BMI, shoe size, and activity level. The ability of the knee to resist angular perturbation at the foot, causing internal rotation, was measured. Male subjects had more stiffness (218%) compared with female subjects (178%), and female athletes from pivot sports had the least increase in knee stiffness.[168]

Familial Tendency to Noncontact ACL Injury

The literature on familial tendency to noncontact ACL injury is sparse. Only 2 studies dealing directly with this subject could be found. In 1994, Harner et al[66] retrospectively

‖References 14, 31, 34, 36, 77, 78, 90, 97, 102, 131, 134.

¶References 10, 34, 39, 78, 96, 97, 111, 158.

reviewed 31 patients who sustained bilateral ACL injuries, comparing them with 23 subjects without a history of past ACL injury (controls) who were matched to injury subjects with regard to age, height, weight, sex, and activity level. These researchers reported a significant difference ($P < .01$) in incidence rate of ACL injuries in immediate family members of 31 patients who sustained bilateral ACL injuries when compared with the incidence of ACL injuries in the immediate family of the 23 control subjects. Eleven of 31 patients who sustained bilateral injuries had a family history of ACL injury (35%), in contrast to only 1 of 23 control subjects (4%). More recently, Flynn et al[49] studied 171 patients with surgically proven ACL injuries and compared them with 171 matched controls. These investigators concluded that when controlled for subject age and number of relatives, patients with ACL tears were "twice as likely to have a relative (first, second, or third degree) with an ACL tear than compared to participants without an ACL tear (adjusted odds ratio = 2.00; 95% confidence interval, 1.19-3.33)."

Summary of Risk Factors for Noncontact ACL Injury

In summary, environmental, anatomical, hormonal, and neuromuscular risk factors, as well as a familial tendency to injury, have all been explored as possible risk factors for noncontact ACL injury. Those at the Hunt Valley II meeting, after reviewing the data on these risk factors, concurred with Meeuwisse's theory,[106] recently expanded by Bahr and Krosshaug,[11] that noncontact ACL injuries frequently occur from a complex interaction of multiple risk factors (Figure 1).

Injury Biomechanics

The mechanics of ACL injury, with an emphasis on the kinematics and kinetics that may predispose female athletes to noncontact ACL tears, has been a focus for research in the sports biomechanics community. In particular, the translational and rotational forces about the knee and motion patterns of the hip, ankle, and the entire kinetic chain have been evaluated with respect to ACL strain. In general, ACL injuries are thought to be associated with abnormal loading of the knee. Dynamic factors that are thought to influence ACL strain are knee kinematics (knee flexion, alignment, and motion in the frontal and transverse planes) and moments about the knee (torque). The primary factors influencing the knee's loading pattern include center of gravity and postural adjustment to rapid changes in the external environment. Anterior cruciate ligament tears are thought to occur with unsuccessful postural adjustments and with the resultant abnormal dynamic loading across the knee. Evidence in support of this concept is seen in studies evaluating the response to perturbed gait, that is, unanticipated cutting. Unanticipated cutting was associated with larger frontal and transverse plane moments when compared with anticipated cutting in a controlled gait study.[14]

Dynamic Loading. Dynamic loading refers to the intersegmental loads transmitted across a joint that change over time and with the flexion angle. The load has both magnitude and direction. Each muscle that crosses a joint generates a load, and this load must be evaluated with respect to the other muscles crossing that joint. The components of dynamic loading include those related to the central nervous system, nerve-muscle interaction, muscle alone, and the joint. Training can modify these.[123] Central nervous system factors involve learned behaviors with an emphasis on patterns of movements and their reactions to "at-risk" positions. The neuromuscular factors include reaction time, motor unit recruitment, and balance (coordination). Muscle factors include those that describe muscle performance rather than the type of muscle contraction. Specifically, muscle performance factors are endurance (fatigue), absolute strength, and the amount of tension and muscle activation pattern. Muscle activation involves time to peak torque, amplitude of the contraction, and the timing of the contraction.

Factors that have a negative effect on dynamic muscle control of the lower extremity are fatigue, decreased torsional stiffness, muscle imbalance, unanticipated cutting, and straight posture on landing (hips and knees near full extension with an upright torso).[#] Factors having a positive effect include anticipation or preparation for cutting, maximum co-contraction of the muscles crossing the knee to increase stiffness, muscle and gait training, agility drills, and plyometrics with the goal to decrease time to peak torque for voluntary contraction. These factors were explored in controlled laboratory and clinical biomechanical studies[14,38,166] (Table 2).

Because training can modify the components of dynamic muscle contraction, there is a plausible means by which the risk of ACL injury may be reduced. This type of training addresses the neuromuscular risk factors by increasing knee stiffness, improving balance, minimizing at-risk positions, and possibly decreasing ACL strain.

Dynamic Activities. Muscle function has been evaluated during dynamic activities, such as cutting and landing from a jump. In general, these gait analysis studies comparing different cohorts of men and women, athletes and nonathletes, have shown that increased hamstring strength, increased knee stiffness, and increased endurance of the muscles crossing the knee are associated with the least anterior tibial translation. High levels of quadriceps activity, hamstring weakness, decreased stiffness, and muscle fatigue are associated with more anterior tibial translation.[169] Muscle fatigue has also been associated with increased errors in segment angular movements.[109]

In a remarkable set of controlled laboratory studies of patients during arthroscopy, Beynnon et al[20] and Fleming et al[47,48] have directly measured in vivo ACL strain of the loaded knee during different activities, including standing, leg extension, and squatting. Anterior cruciate ligament strain varies with flexion angle and activity. High ACL strain rates were documented with the knee near full extension and with quadriceps or isometric hamstring contraction. Low ACL strain rates were noted with the knee flexed less than 50° and with hamstring or isometric quadriceps contraction. Cerulli et al[27] and Lamontagne et al[87] also measured in vivo ACL strain in a hop-stop task in their controlled laboratory studies. Their results also show that the peak ACL strain

[#]References 14, 51, 74, 77, 105, 109, 168, 169.

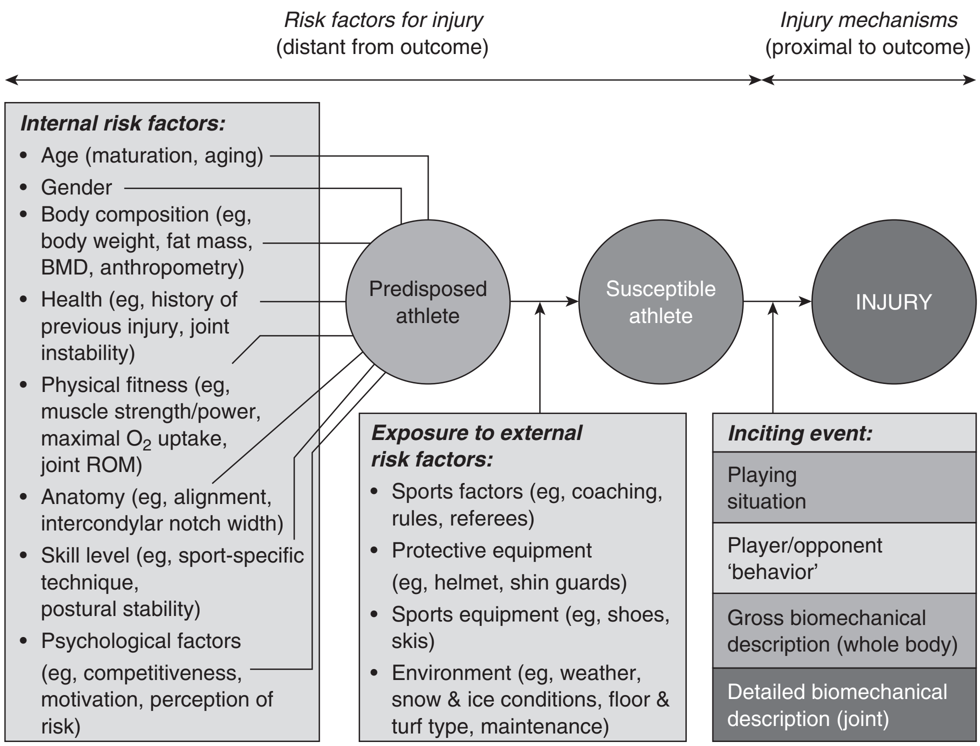

Figure 1. A comprehensive injury causation model developed by Bahr and Krosshaug[11] based on the epidemiologic model of Meeuwisse[106] and the biomechanical model of McIntosh.[101] BMD, bone mineral density; ROM, range of motion. Printed with permission from *Br J Sports Med*. 2005;39:327.

occurred at the smallest knee flexion angle. Their results also show that the peak ACL strain was coincident with the peak impact ground reaction forces.

Describing ACL Injury. Bahr and Krosshaug[11] suggested that descriptions of ACL injury should include at least 4 elements: vital aspects of the playing situation (sports-specific details), athlete and opponent behavior (action and interaction with the opponent), gross biomechanical characteristics (whole-body biomechanics), and detailed biomechanical characteristics (joint/tissue biomechanics). The player's description of the injury from memory or from what observers tell him or her may be incomplete or flawed. Videotapes of the injury are helpful, even when the quality of the image is poor. Analysis of athlete interviews and videotapes shows that the majority of ACL noncontact injuries occur at the time of landing or deceleration in basketball and at the time of side-step cutting in team handball. The position of the leg at the time of injury displays tibial rotation, apparent knee valgus, foot pronation, and a relatively extended knee and hip.[6,9,60,104,119,125,156]

In alpine skiing, video analysis has documented 2 mechanisms of injury distinct from sports with running. When the knee is flexed beyond 90° and the tibia is internally rotated, an internal torque appears to occur about the long axis of the tibia, resulting in ACL injury.[42] In the second mechanism, internal tibial torque occurs with the knee in full extension, resulting in injury.[65]

Retrospective reviews of injuries in dancers and ice skaters reveal few ACL noncontact injuries.[22,122,163] These athletes display excellent trunk control. Their training emphasizes core strength, balance, and agility. They land on their toes with their lower extremity externally rotated and, in the case of ice skaters, with little shoe-surface resistance. Most jumps end on a flexed knee; skaters often land skating backward. Because most moves are choreographed and practiced, the response to unanticipated or perturbed movement is an uncommon occurrence.

Prevention Programs

Most prevention programs are based on altering dynamic loading through neuromuscular training. Silvers[147] summarized the 12 prevention programs that had published data regarding their trials at the time of the Hunt Valley II meeting (Table 3). The components of the programs are compared, and the strengths and weaknesses of each program are evaluated. A meta-analysis of 6 of these programs has recently been compiled by Hewett et al.[71]

No prevention program has resulted in an increased incidence of ACL injuries. Most have reported a decrease in the rate of knee injuries in the intervention group.** Unfortunately, few studies evaluating the effectiveness of these programs in decreasing knee injuries are randomized controlled trials. Most are nonrandomized, and several are even uncontrolled. Some studies examined the rate of knee injuries in their population,[68,70,126,164] and others evaluated the effect of their program on the rate of noncontact ACL

**References 25, 42, 55, 63, 68, 70, 98, 118, 126, 164.

TABLE 2
Dynamic Muscle Control on the Knee: Positive and Negative Factors[a]

Factor	Comment	Citation
Negative		
Fatigue	Increased anterior translation of 32.5%	Wojtys et al[169] (1996)
	Increased angular error after running	Miura et al[109] (2004)
Stiffness	Decreased torsional stiffness in females compared with size- and sport-matched controls	Wojtys et al[168] (2003)
Muscle-imbalance sport, previous training	Quadriceps predominance	
Unanticipated cutting	Internal/external rotations and varus/valgus moments up to 2 times greater	Besier et al[14] (2001)
Jump-landing posture	Straight knee posture in females	Huston et al[77] (2001)
	Differences between athletes: less ankle and hip extension; moments in recreational athletes	McNitt-Gray[105] (1993)
Positive		
Anticipator effects	Preparing/anticipating for running and cutting decreases varus/valgus and internal/external rotation moments 2-fold	Besier et al[14] (2001)
Maximal co-contraction to increase stiffness	Decreases anterior tibial translation; increases stiffness 379% in men, 212% in women	Wojtys et al[166] (2002)
Muscle training		
Muscle activation	Improved timing; higher amplitude	Wojtys et al[169] (1996)
Gait pattern alteration	Knee hyperextension gait abnormalities in unstable knees; recognition and preoperative gait training	
Agility	Improved spinal reflex and cortical response times; sport, activity specific	
Plyometrics	Increased voluntary contraction; decreased time to peak torque	

[a]Printed with permission from DeMaio.[38]

injuries specifically.[††] Some had cohorts too small to effectively evaluate ACL injury rate.[63,133,152,164] The mode and vehicle of instruction of the programs vary from program to program. Compliance within the program is often not reported. The age group participating in the program varies from program to program as does the sport surveyed. Most programs have been tested on only female athletes.

It appears that all successful programs have one or several of the following components: traditional stretching and strengthening activities, aerobic conditioning, agilities, plyometrics, and risk awareness training. Garrett has nicely outlined in Table 4 the components of present-day prevention programs, stressing the congruence between these programs and the research on risk factors and mechanism of injury.[53] The rationale to include plyometric exercises is based on evidence that the stretch-shortening cycle activates neural, muscular, and elastic components and, therefore, should enhance joint stability (dynamic stiffening). Indeed, plyometric exercises, combined with other training exercise, have been found to decrease landing forces, decrease varus/valgus moments, and increase effective muscle activation. Balance and postural exercises stimulate the somatosensory systems and therefore should stimulate coactivation and joint stiffness. Movement and awareness training, including cognitive training, kinesthesia visualization, verbalization, and feedback, should provide more efficient biomechanical positioning for protective mechanisms, reducing joint moments and ACL loading.

In addition, movement and awareness training helps the athlete cope with unanticipated movements, and perturbation training appears promising for stimulation of corrective activation patterns. The muscle-strengthening objective is to improve quality of muscle function. Core strength as well as hamstring and quadriceps strength should be emphasized. A higher ratio of hamstring-to-quadriceps strength

[††]References 25, 42, 55, 63, 68, 98, 118, 133, 152.

TABLE 3
Prevention Programs[a]

No.	Author	Sport	N	Duration	Sex	Random	Equipment	Strength	Flexibility	Agility	Plyometrics	Proprioception	Program/Study Strengths	Program/Study Weaknesses	Outcome
1	Griffis et al[63] (1989), S	Basketball	Not reported; 2 teams	8 years	Female	No	Jump box, balance	No	No	Yes	No, landing technique	Yes, deceleration pattern (3-step shuffle)	Changing deceleration and landing technique (encouraged knee and hip flexion)	Not randomized; unpublished	89% decrease in noncontact ACL injury
2	Ettlinger et al[42] (1995)	Alpine skiing	T, 4000; C, not specified	1 year with 2 years of historic controls	Male/ female	No	Video clips of skiers sustaining ACL injuries and those who avoided injury in very similar falls	No	No	No	No	No	Nonrandomized, controlled, interventional study; large number of injuries	Nonrandomized; not all potential participants trained; historic controls; exact description of knee sprain not always available; exact exposure to risk not precisely determined	Severe knee sprains were reduced by 62% among trained skiers (patrollers and instructors) compared to unperturbed group who had no improvement during the study period
3	Caraffa et al[25] (1996)	Soccer	T, 300; C, 300	3 seasons	Male	No, prospective	Balance boards	Proprioceptive neuromuscular facilitation exercises	Yes	No	No	Yes, balance board activities (multilevel)	Mechanoreceptor/ proprioceptive training	Additional equipment; not cost effective on large-scale basis	87% decrease in noncontact ACL injury; 1.15 rate reduced to 0.15/1000 athlete exposures
4	Hewett et al[70] (1999), A	Basketball, volleyball, soccer	1263	1 year	Male/ female	Yes	Jump box; balance	Yes	No	No	Yes	Yes	Decreased peak landing forces; decreased valgus/varus perturbations; increased vertical leap; increased hamstrings strength and decreased time to contraction	One-on-one program in sports facility; not feasible to implement across large cohort	Female injury rates of 0.43 to 0.12 (male, 0.9) over 6-week program; untrained group of 3.6 to 4.8 higher rates of ACL injury
5	Heidt et al[68] (2000), A, S	Soccer	300	1-year intervention (7-week period)	Female	No	Sports cord; box jump	Yes	No	Yes	Yes	Yes	Increased strength; lower overall injury rates	Not statistically significant; 7 weeks was insufficient for neuromuscular education to occur at mechanoreceptor level	61.2% injuries in knee/ankle; 2.4% injury rate in intervention versus 3.1 in control

(continued)

TABLE 3
(Continued)

No.	Author	Sport	N	Duration	Sex	Random	Equipment	Strength	Flexibility	Agility	Plyometrics	Proprioception	Program/Study Strengths	Program/Study Weaknesses	Outcome
6	Soderman et al[152] (2000), S	Soccer	T, 121; C, 100	1 season (April-October)	Female	Yes	Balance board in addition to regular training	No	No	No	No	Yes, balance	Randomized	Small N; low overall injury incidence; 37% dropout rate; not all subjects received same amount of training; unknown whether additional training was controlled	Intervention did not reduce risk of primary traumatic injuries to lower extremities; 4 of the 5 ACL injuries in total sample occurred in intervention group
7	Myklebust et al[118] (2003)	Team handball	900	3 years	Female	No	Wobble board; balance foam mats	No	Yes	Planting neuromuscular control	No, landing technique	Balance activities on mats and boards	Compliance to program monitored; instructional video	Not randomized	In elite team division, risk of injury was reduced among those who completed program (odds ratio, 0.06 [0.01-0.54]) compared with control; overall reduction of ACL injury
8	Wedderkopp et al[164] (2003), A, S	Team handball	236	10 months	Female	Yes, cluster randomized controlled trial	Balance board (proprioceptive) in 4 levels	No	No	Yes	Yes	Balance training with ankle disks	Randomized controlled trial	Injury types not specified; description of ankle disk training not provided; intervention group also did "warm-up" exercises but not specified; compliance not assessed	Ankle injuries were significantly greater in control group (2.4 vs 0.2); unspecified knee injuries were not significantly less in trained group (0.9 vs 0.6); 5 knee sprains and 1 knee "subluxation" in control group versus 1 knee sprain in trained group

(continued)

TABLE 3
(Continued)

No.	Author	Sport	N	Duration	Sex	Random	Equipment	Strength	Flexibility	Agility	Plyometrics	Proprioception	Program/Study Strengths	Program/Study Weaknesses	Outcome
9	Gilchrist et al[55] (2004)	Soccer	561	1 year	Female	Yes	Cones, soccer ball	Yes, gluteus medius abduction, extension, hamstrings; core	Yes	Deceleration; sport specific	No, landing technique; multiplanar	Strength on-field perturbation on grass	Instructional video, Web site, compliance monitored (random site visits)	1-year intervention; began on day 1 of season	Overall 72% reduction in ACL injury: 100% reduction in practice contact and noncontact ACL injuries; 100% reduction in contact and noncontact ACL injuries in last 6 weeks of season
10	Pfeiffer et al[133] (2004)	Soccer	1439	9-week treatment	Female	No	No	No	Yes	Cut, neuromuscular control	No, landing technique	No	Compliance monitored; significant reduction in peak vertical impact force and rate of force development in intervention	No decrease in injury; intervention performed at end of training; possible fatigue phenomenon	6 noncontact ACL injuries: 3 in treatment and 3 in control = no direct effect
11	Mandelbaum et al[98] (2005)	Soccer	T, 1041; C, 844	2 years	Female	No, voluntary enrollment	Cones, soccer ball	Hamstrings, core	Yes	Soccer specific with deceleration technique	No, landing technique; multiplanar	Strength on-field perturbation on grass	Instructional video, Web site; compliance monitored	Not randomized; inherent selection bias	Injury rates: year 1, 88% reduction in noncontact ACL injury; year 2, 74% reduction in noncontact ACL injury
12	Olsen et al[126] (2005), A	Team handball	1837	1 year	Male/ female	Yes, cluster randomized controlled trial	Wobble board; balance foam mats	Yes	Yes	Cut, neuromuscular control	No, landing technique	Balance activity on mats and boards	Randomized; compliance monitored; reduction of injury	Efficacious component(s) of intervention not known	129 acute knee and ankle injuries overall; 81 in control (0.9 overall, 0.3 training, 5.3 match) versus 48 injuries in intervention (0.5 overall, 0.2 training, 2.5 match)

[a]A, ACL injuries not specifically assessed; S, sample size relatively small (power inadequate?). Reprinted with permission from Silvers.[147]

TABLE 4
Components of a Prevention Program[a]

The Risk	The Strategy	How?
Extended knee	Flexed knee	Soft landing
Extended hip	Flexed hip	Soft landing
Knee valgus	Minimal valgus	Control on landing
Loss of balance	Improve balance	Dynamic balance training
Poor skill	Improve agility	Agility skills

[a]Printed with permission from Garrett.[53]

should reduce shear.[34] Dynamic neuromuscular training may also facilitate neuromuscular adaptation that protects the athlete's ACL from increased loading.

Only 2 published programs have not resulted in a decreased rate of knee injuries. Using balance board training, Soderman el al[152] followed female soccer players in Sweden for 1 season and found no decrease in noncontact ACL injuries. However, the study did not have adequate power, and the program's drop-out rate was 37%. Pfeiffer et al,[133] surveying high school girls playing soccer, basketball, and volleyball, in Boise, Idaho, over a 2-year period, found no difference in injuries between trained and untrained populations. The mean incidence of noncontact injuries in the control group was 0.078, compared with 0.167 in the intervention group. Unfortunately, this program, like the study of Soderman et al,[152] lacked adequate power. Moreover, it used a posttraining ACL injury prevention protocol using strength and plyometrics; it has been theorized that perhaps the fatigue phenomenon diminished some of the protective benefit of using this program.[133]

Although all programs analyze their results with regard to the program's ability to decrease knee injury, few have tried to analyze the program's effect on performance and alteration of risk factors. Hewett et al[74] found that the Sportsmetrics program increased vertical jump; improved hamstring strength, power, and peak torque (13% dominant side and 26% nondominant side); and improved controlled dynamic loading of the knee.

Holme et al[75] investigated the effects of a training program on posture control, knee muscle strength, and landing techniques of female team handball players. The training program consisted of floor exercises, wobble board exercises, and balance mat exercises done over a 5- to 7-week period. The floor exercises emphasized the landing techniques, whereas the wobble board exercises and balance mat exercises focused on posture control. The results of this study demonstrated that subjects had significant improvement in their 2-leg balance index but no significant changes in muscle strength and knee function testing scores 8 weeks after the start of the training program. In addition, after training, these same investigators found no improvement in the threshold to detect passive knee motion (proprioception).

Paterno et al[132] also studied the effects of training on single-leg posture control of young female athletes. Their training programs consisted of exercises emphasizing hip and trunk strength, plyometric and dynamic movement training, and resistance training over 6 weeks. The study demonstrated that subjects had significant improvement of single-leg posture control in the anterior-posterior direction but not in the medial-lateral direction. Irmischer et al,[80] in a randomized controlled trial evaluating the effects of a training program consisting of jump-landing tasks, reported that participants in the program demonstrated significantly decreased peak vertical ground reaction force and rate of development of peak ground reaction force on landing, and Chimera et al,[33] in a control group design, reported increased preparatory adductor activity and abductor-to-adductor coactivation after plyometric training. To date, no one has analyzed his or her program's effect on increasing quadriceps power or speed or improving a player's agility, flexibility, or coordination.

In summary, presently there is insufficient although encouraging evidence supporting the premise that ACL prevention programs improve performance and/or alter what are thought to be key risk factors for injury. However, limited studies have been published. Those published have had moderate sample sizes with frequently no control group data. On the other hand, various forms of training not related to ACL injury prevention have been shown in the past to improve the basic component of sports performance. Resistance training improves strength; plyometric training improves power; flexibility exercises improve range of motion. Therefore, it is logical to assume that ACL injury prevention programs should be able to accomplish the same results. Moreover, Garrett[53] has suggested that one should consider evaluating not only alterations in single parameters such as strength, power, and flexibility but also the resultant alterations in motor skill development provided by agility, balance, and plyometric exercise.

Little has been done on investigating the ideal duration of a prevention program. Because injuries can occur at the beginning of training, it would seem reasonable that these programs should be instituted before the beginning of the season and before the beginning of intense-contact practice sessions. Some suggest that athletes need a minimum of 6 weeks of training. Six weeks does correlate with the time frame needed for increased motor recruitment but not that needed for muscle hypertrophy or improved endurance. However, the programs are effective because they train nerve-muscle factors, and perhaps 6 weeks is adequate. Deconditioning after termination of the program appears to happen quickly. In fact, aerobic deconditioning has been reported to occur in 1 to 2 months[113] and anaerobic deconditioning in as brief a time as 2 weeks.[59] This finding would imply that prevention programs would need to be ongoing throughout an athlete's career.[124]

Some prevention programs have been designed to be done on the field of play as an alternate warm-up program by the entire team, whereas others are laboratory exercises instituted before the beginning of the season and are aimed at small-group instruction. Which style of training program is most appropriate has not yet been determined. Some investigators have suggested that perhaps both programs are needed; that is, all members of the team could participate in the on-the-field alternative warm-up program, whereas athletes found on screening to be at higher risk for injury based

TABLE 5
Consensus Statements: 2005 Hunt Valley II Meeting

Introduction

- The global incidence of ACL injuries remains high. The incidence of noncontact ACL injuries appears to be greatest in the young. The incidence of noncontact ACL injuries appears to be greater in the female than in the male population.
- Data support the fact that despite surgical stabilization of ACL injuries, knee posttraumatic arthritis frequently develops in the young athlete who sustains this injury. Therefore, a continued emphasis on improving prevention programs is needed to increase their effectiveness. This requires understanding their effect and influence on injury biomechanics and risk factors for injury.

Risk factors

- The effect of estrogen or any other hormone on injury rate is not yet well defined, but there does appear to be an uneven distribution of injuries during the monthly cycle of the female, which suggests hormonal involvement.
- Although the preponderance of evidence would indicate it is in the early and late follicular phases in which the greatest numbers of injuries occur, the evidence is not conclusive.
- With regard to anatomical factors associated with injury, there is no definite evidence that any anatomical factor is reliably associated across age groups and sexes with an increased rate of injury.
- In a select, athletic, college-aged population, a combination of increased body mass index, narrow notch width, and increased joint laxity, as defined by KT-2000 arthrometer or hyperlaxity measures, is directly correlated and predictive of ACL injury.
- We need to better understand the role of knee valgus or, perhaps more precisely, "apparent knee valgus" on ACL injury rates.
- The position of hip and knee extension is likely to be associated with a greater risk of injury.

Biomechanics of injury

- The incidence of noncontact ACL injuries remains greater in sports requiring rapid deceleration during cutting, pivoting, landing, and change in direction (eg, soccer, basketball, European team handball, netball, and gymnastics).
- The mechanism of noncontact ACL tears is not clearly understood; however, existing evidence points to a combined loading pattern as being most detrimental with respect to injury (ie, combined loading in the sagittal, frontal, and transverse planes). That is to say, tibial anterior translation, knee valgus-varus moments, and knee internal/external rotation moments are contributors to dynamic ACL loading.
- Movement patterns that produce valgus and varus or extension moments, especially when the knee is only slightly bent, appear to increase risk.

Prevention programs

- There is good level 2 evidence that neuromuscular training including plyometrics, balance, and technique training, as well as a heightened awareness of injury biomechanics, reduces the risk of serious knee injuries in female athletes. What specific exercises or sequence of exercises or what intensity and duration of exercise are most important is still unknown.
- All reported prevention programs for ACL noncontact injuries center on alteration of neuromuscular risk factors, but each is unique. Some are sport specific; some are general; some are age specific; some are not. Most have been designed for and tested with female athletes.
- The underlying mechanism by which intervention programs are effective is not clearly understood; however, existing evidence points to changes in balance, strength, and neuromuscular coordination as being possible contributors.
- Training may facilitate neuromuscular adaptations that provide increased joint stabilization and muscular preactivation and reactive patterns that may protect the athlete's ACL from increased loading.

Future initiatives

- Researchers should continue to evaluate existing prevention programs through conducting additional randomized controlled trials between institutions in various geographic areas of the country and across all age groups and both sexes for all high-risk sports.
- Research design should strive to identify which of the components of present-day prevention programs are most significant in decreasing the rate of noncontact ACL injuries.
- Evaluate the effect of each component of prevention programs on strength of key muscle groups, on muscular firing patterns, and on altering landing, cutting, and pivoting techniques.
- Strive for further clarification of "at-risk factors."
- Enhance awareness of prevention strategies within the "at-risk" population.
- Establish a national and an international ACL registry for all ACL injuries similar to that which exists in Norway.

on identification of neuromuscular risk factors might also participate in laboratory-structured small-group programs. Little data, however, exist as to the effectiveness of one style program over another. Moreover, little data exist regarding the feasibility and effectiveness of screening the "at-risk" population. A yet unanswered question is do we have enough information to select the "at-risk" population?

Further information regarding the duration of programs and the volume, intensity, and degree of retention of each program is needed. The age at which athletes should start prevention programs remains unclear. Because many of these injuries occur in women during the middle to late teenage years, early adolescence seems like an appropriate time to institute programs. Whether programs are more effective when they are sport specific rather than mechanism specific is not clear.

Also needed are effective strategies to disseminate and integrate information on prevention programs within junior high schools, high schools, colleges, and professional athletic programs, as well as within recreational athletic programs, so that athletes of all ages can benefit from this knowledge. Enlisting the aid of other sports medicine organizations such as the National Athletic Trainers Association, the American Academy of Orthopaedic Surgeons, and the American College of Sports Medicine, as well as sports organizations such as the National College Athletic Association, the Amateur Athletic Union, the National Basketball Association, and the National Soccer Association, to help with the task of developing dissemination and integration strategies appears critical.

In summary, there is good level 2 evidence that neuromuscular training, including strengthening and flexibility exercises, plyometrics, agilities (balance), and technique training, as well as a heightened awareness of the biomechanics of injury, reduces ACL injury risk in female athletes. What specific exercise or sequence of exercises, what intensity or duration of exercises, or when to initiate the exercises is still unknown. Randomized trials are underway to determine the longitudinal effect of initiating prevention programs at an early age. The impact of ACL prevention programs is still largely unknown. Needed are more randomized controlled trials between institutions, between various geographic areas of the country, across all age groups, and across both sexes for all high-risk sports, followed by a careful analysis of the effect of these prevention programs on influencing dynamic knee stability, sport performance, and overall injury rates. Table 5 summarizes the consensus statements formulated by the Hunt Valley II participants. They reflect not only recent research advancements but also still unanswered questions.

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