Noncontact Anterior Cruciate Ligament Injuries: Risk Factors and Prevention Strategies

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Abstract

An estimated 80,000 anterior cruciate ligament (ACL) tears occur annually in the United States. The highest incidence is in individuals 15 to 25 years old who participate in pivoting sports. With an estimated cost for these injuries of almost a billion dollars per year, the ability to identify risk factors and develop prevention strategies has widespread health and fiscal importance. Seventy percent of ACL injuries occur in noncontact situations. The risk factors for noncontact ACL injuries fall into four distinct categories: environmental, anatomic, hormonal, and biomechanical. Early data on existing neuromuscular training programs suggest that enhancing body control may decrease ACL injuries in women. Further investigation is needed prior to instituting prevention programs related to the other risk factors.

J Am Acad Orthop Surg 2000;8:141-150

Significant advances in the diagnosis and treatment of anterior cruciate ligament (ACL) injuries were made during the 1970s and 1980s. In the 1990s, attention focused on identifying noncontact injury mechanisms in an effort to define risk factors for injury. The ultimate goal of defining the risk factors was the development of effective injury prevention programs. In a 1999 review of the epidemiology of ACL injuries, Garrick noted that "of the 3,572 Medline citations under the ACL topic heading, only 133 are subheaded 'prevention' and less than 10 of these deal with prevention of the injury rather than prevention of some surgical complication" (J. G. Garrick, MD, unpublished data, 1999).

General population studies of the incidence of this injury are somewhat misleading as to its societal significance. For instance, in a study of the incidence of ACL injuries in a large managed-care–insured population, Daniel and Fritschy[1] reported an annual rate of one ACL injury per 3,500 enrollees. Projecting this rate across the United States yields only about 80,000 injuries per year. However, certain segments of the population (the very young, the elderly, and those who are sedentary) rarely sustain this injury. In the study by Daniel and Fritschy, the average age of those with ACL sprains was 26, and virtually every study of ACL reconstructions has noted that the average age is in the third decade of life. Consistent with other authors, Daniel and Fritschy also reported that 70% of the injuries were the result of sports participation. Therefore, it appears that the vast majority of ACL injuries occur during a 30-year period (15 to 45 years of age)—a period that encompasses roughly 47% of the population of the United States. During those three decades of life, the annual incidence of ACL injuries is one injury for every 1,750 persons.

The information in this article was derived in part from discussions at the Hunt Valley Consensus Conference on Prevention of Noncontact ACL Injuries (conducted under the joint sponsorship of the American Orthopaedic Society for Sports Medicine, the Orthopaedic Research and Education Foundation, the National Athletic Trainers Association Research and Education Foundation, and the National Collegiate Athletic Association), Hunt Valley, Md, on June 10, 1999.

One or more of the authors or the departments with which they are affiliated have received something of value from a commercial or other party related directly or indirectly to the subject of this article.

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Because of the greater absolute number of male participants in sports activities, more males than females sustain this injury. However, National Collegiate Athletic Association statistics show that in those activities in which males and females both participate, with similar rules and equipment (e.g., soccer, basketball, volleyball), the likelihood of sustaining an ACL injury is two to eight times greater for females than for males.[2] No investigator has found any evidence of systematic bias that might be responsible for this difference; thus, it would appear that, at least in these sports, females are more likely to sustain this particular injury, even though the preponderance of male participation in these and other sports results in more males actually being injured.

Approximately 50,000 ACL reconstructions are done each year,[3] at an approximate cost of $17,000 per procedure; therefore, the financial impact is just under a billion dollars ($850,000,000). This figure does not take into account the cost of the initial care of all ACL injuries or the conservative management and rehabilitation of the patients who do not undergo ACL reconstruction. Moreover, it does not consider the economics of the future—that is, the cost of treating the long-term complications of the posttraumatic degeneration that occurs in many patients who sustain ACL injuries, even those who undergo reconstruction. Considering not only this economic loss but also the significant emotional and physical burden this injury inflicts on the individual who sustains it, efforts toward developing prevention strategies seem prudent.

Etiology

Approximately 30% of all ACL injuries result from direct contact with another player or object (R. A. Malinzak, MD, unpublished data, 1999). Although several authors have speculated on the etiology of the 70% of ACL injuries that do not result from direct contact, the basic mechanism for this injury still eludes us. Activities that appear to be associated with significant risk include decelerating and pivoting, awkward landings, and "out of control" play. Potential risk factors that have been identified as associated with noncontact injuries can be classified as environmental (e.g., equipment, shoe-surface interactions), anatomic (e.g., knee angle, hip angle, laxity, notch size), hormonal, and biomechanical (e.g., muscular strength, body movement, skill level, neuromuscular control).

Environmental Risk Factors

Role for Knee Braces

During the late 1970s, prophylactic knee braces were introduced to protect the collateral ligaments. Some braces had a unilateral hinge and were taped or strapped in place; others had bilateral hinges incorporated into an elastic or neoprene sleeve. Early reports indicated a decrease in the number of knee injuries in braced collegiate and high school athletes.[4] Later studies, however, did not confirm this finding; in fact, several studies even reported an increase in the number of knee injuries in braced athletes.[5,6] In 1984, the American Academy of Orthopaedic Surgeons issued a position statement on knee braces, in which it was noted that there was no definitive evidence that prophylactic knee braces can prevent knee injuries.

Despite such negative reports, high school, college, and professional players continue to use prophylactic

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bracing, citing psychological and unmeasured proprioceptive benefits. Németh et al[7] showed that functional braces do modify electromyographic activity and timing. However, the significance of this finding has yet to be fully explored. Because of the many variables that must be considered (e.g., position played, condition of playing surface, skill and experience of the player, effect of rule changes, influence of coaching), a study to evaluate the effectiveness of braces on ACL injury rates requires a large sample size and a study population that is homogeneous enough to yield statistically significant information.

Influence of Shoe-Surface Interaction

Many of the early studies assessing the influence of the playing surface on ACL injury lacked adequate controls on variables such as surface (e.g., hardness, age, weather conditions) and shoe type. The surface was viewed as the sole contributor to injury, despite the fact that the friction associated with a foot-plant injury must involve two surfaces. More recently, a high level of friction between shoes and the playing surface has been identified as a major risk factor for noncontact ACL injury in the sport of team handball.[8] In football, cleat design has not only been found to be an important factor in torsional resistance in the laboratory; it has also been found to influence ACL injury rates.[9] Noncontact ACL injuries appear to occur most frequently when playing surfaces are dry.[10]

Shoe-surface considerations not only must center on the complex nature of that relationship, with its many contributing factors (e.g., axial load, weather conditions), but also must deal with the balance between performance and safety. Higher levels of friction between the shoe and the surface are generally associated with better performance but a higher injury risk. Hence, a shoe-surface design that results in a safer environment may not allow optimal performance.

Anatomic Risk Factors

There are obvious anatomic differences in lower-extremity alignment, joint laxity, and muscle development between males and females. Less obvious are the differences in femoral notch and ACL size. Static measurements of lower-extremity alignment (e.g., hip varus, knee valgus, foot pronation, hip rotation) can be made, but the real question is which differences, if any, contribute to an increased risk of ACL injury.

There is increased femoral anteversion, increased Q angle, excessive tibial torsion, and excessive foot pronation in the female (Fig. 1). However, the influence of these variables on functional movement patterns has not been fully explored. Such information is critical for relating these variables to risk factors for ligament injury. In a brief preliminary report, Meister and co-workers compared the thigh-foot angle in a group of 51 ACL-injured female athletes with that in a matched cohort of 65 uninjured female athletes and found that an increase in the thigh-foot angle may be a risk factor for noncontact ACL injuries, but that femoral anteversion was not (K. Meister, MD, unpublished data, 1999).

Laxity (the combination of joint hypermobility and musculotendinous flexibility) is more prevalent among women than men.[11] Joint hypermobility appears to be a genetically inherited trait, but musculotendinous flexibility can be altered through conditioning. A number of studies exploring the relationship of hypermobility or laxity to injury have been reported, with conflicting results.[12-14] In a profiling study of noncontact ACL basketball injuries during the 1998-1999 NCAA season, no evidence of hyperlaxity or tight hamstrings was evident in either male or female athletes (E. A. Arendt, MD, unpublished data, 1999).

There is a mild increase in both anterior and posterior knee laxity (18% to 20%) when certain sports (basketball and jogging) are performed for more than 30 minutes.[15] This increased laxity returns to normal after 60 minutes. Such data raise the issue of whether there could be a relationship between exercise-associated increased laxity, which is considered to be a normal physiologic response to exercise, and subsequent ligamentous injury. At present, the relationship between hypermobility and knee-ligament injuries is still unresolved.

Of the 15 published studies on the relationship of the femoral notch to ACL injuries, 9 address gender differences (E. A. Arendt, MD, unpublished data, 1999). De-

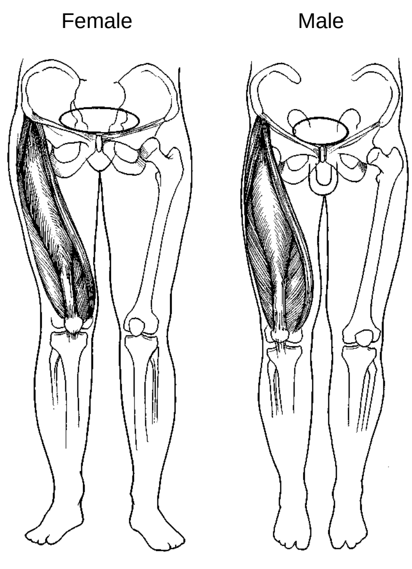

Figure 1 In general, when compared with men of equal ages, women have wider pelvises as well as greater hip varus, knee valgus, and foot pronation.

spite the limitations of the various measurement techniques and the potential lack of a controlling leg rotation, the literature supports the following general statements: (1) The notch width (regardless of measurement technique) in patients with bilateral ACL injuries is less than that in patients with unilateral ACL injuries. (2) The notch width in knees with bilateral and unilateral ACL injuries may be less than that in normal control subjects. (3) On average, the width of the notch is less in females than in males. (4) On average, the notch width index (relation of condylar width to notch width) in females is less than that in males. (5) There is a relationship between the total width of the condyles and the width of the notch; the smaller the femur, the smaller the notch. (6) There is too much variability in measurement techniques used in the various published studies to allow definitive statements concerning either the size of the ACL within the notch or the relationship of notch width to unilateral ACL injury.

In summary, the association of anatomic variables with an increased risk for ACL injury is intriguing, but to date no anatomic variable has been directly correlated with an increased risk for unilateral noncontact ACL injury.

Hormonal Risk Factors

The possible role of hormones in predisposing female athletes to injury of the ACL has recently been an area of active investigation. In 1996, estrogen and progesterone receptor sites were found in human ACL cells,[16] suggesting that female sex hormones may play a role in ACL structure. Several researchers have since determined that female sex hormones can influence the composition and mechanical properties of the ACL.[16,17] For example, both fibroblast proliferation and the rate of collagen synthesis are reduced with increasing estradiol concentrations,[16] and the administration of estrogen reduces the tensile properties of rabbit ACL.[17]

Several investigators have attempted to link hormone fluctuations during the menstrual cycle to the rate of ACL injuries, but with conflicting results. Wojtys et al[18] reported more injuries than expected in the ovulatory phase of the menstrual cycle (days 10 to 14, when estrogen levels surge); fewer injuries occurred in the follicular phase (days 1 to 9, when estrogen and progesterone levels are low). Myklebust et al[19] found fewer injuries during the midcycle estrogen surge (days 8 to 14) in a group of Norwegian team handball players. The difference in the findings of these two studies is likely related to an important difference in the patient populations. Wojtys et al examined women with regular menstrual cycles who were not taking oral contraceptives; in contrast, half of the subjects in the study by Myklebust et al were taking oral contraceptives. Oral contraceptive use has been previously linked to lower injury rates in women[20]; however, the injuries in these studies were classified only as general traumatic injuries and did not isolate knee or ACL injuries. A 1998-1999 survey of 103 ACL-injured female NCAA basketball players found that athletes tended to be injured just before or after the onset of menses, regardless of their use of oral contraceptives (E. A. Arendt, MD, unpublished data, 1999).

Although the results of studies so far are compelling regarding the interaction between female hormone concentrations and compositional changes to the ACL, consensus is lacking regarding the relationship of menstrual cycle phase to the incidence of ACL injuries. In light of this lack of agreement, more rigorous studies must be performed before treatment or prevention recommendations can be made.

Biomechanical Risk Factors

Role of Proprioception and Neuromuscular Control in Joint Stability

The term "functional joint stability" refers to the joint stability required to perform a functional activity. This stability is provided by both static and dynamic stabilizers in varying degrees depending on the activity. The dynamic contributions emerge from precise neuromotor control over the skeletal muscles crossing the joint. Skeletal muscle activation may be conscious (initiated directly by voluntary command) or unconscious (initiated automatically as part of a motor program or in response to sensory stimuli).

The term "neuromuscular control" specifically refers to unconscious activation of the dynamic restraints surrounding a joint in response to sensory stimuli. In 1906, Sherrington initially described proprioception as the afferent information arising from the periphery concerning regulation of postural equilibrium, joint stabilization, and several conscious peripheral sensations.[21,22] Proprioception is the sensory source best suited for providing the information necessary for mediating neuromuscular control, thereby enhancing functional joint stability.

Sources of proprioceptive information include mechanoreceptors located in muscular, articular, and cutaneous tissues that are responsible for transducing mechanical events into neural signals. The stimuli recorded by these receptors are conveyed via afferent neurons to the spinal cord. Many afferent neurons bifurcate, with the projections synapsing directly with gamma motor neurons, alpha motor neurons, or interneurons. Some interneurons provide the basis for sensory integration and motor control at the spinal level; others form the ascending tracts leading to higher central nervous system structures. The spinocerebellar pathways probably provide the organizational core of supraspinal control over the dynamic restraints, which is an element of functional joint stability. Working subconsciously, the cerebellum has an essential role in planning and modifying motor activities by comparing the intended movement with the outcome movement.[23] Continual inflows of information from the motor control areas and central and peripheral sensory areas provide the means by which the cerebellum can accomplish this task (Fig. 2).

Control over the dynamic restraints, independent of the motor control level, can be considered to occur both in preparation and in response to external events. Preparatory actions occur on the identification of the beginning of an impending event or stimulus as well as its effects, whereas reactions occur in direct response to sensory detection of effects from the arrival of the event or stimuli.[23] Both forms of control have unique but interrelated roles in control over the dynamic restraints.

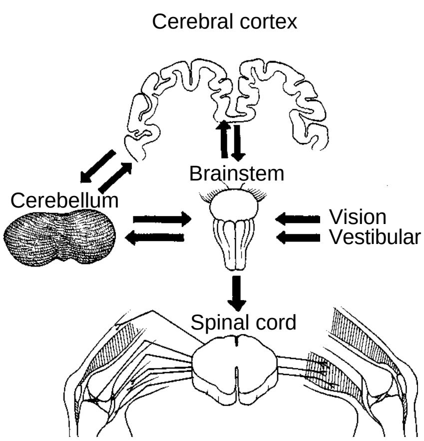

Figure 2 The role of proprioception in mediating neuromuscular control of joint stability. (Adapted with permission from Lephart SM, Fu FH [eds]: *Joint Stability*. Champaign, Ill: Human Kinetics, 2000.)

Proprioception plays an integral role in maintaining functional joint stability. Appropriate adaptations to preparatory activation of muscle, mediated by proprioceptive signals, may provide the most efficient means of inducing prophylactic mechanisms that could shield the ACL from extreme in vivo forces and reduce the incidence of ACL injury in the female athlete.

Hip-Trunk Contributions to ACL Injury

Gender differences have been found in motion patterns, positions, and forces generated from the hip and trunk to the knee. These differences are important because hip position and motion influence knee position, loads, and stiffness,[24-26] and the moment that is developed at the knee has been characterized as being "slaved" to the moment produced at the hip.[27] The largest single contributor to production of motion, stabilization of position, and development of moments of any joint or body segment is coordinated muscle activation.[25] Females have been shown to have both less hamstring and less gluteus medius activation than males (W. B. Kibler, MD, unpublished data, 1999; L. J. Huston, MS, unpublished data, 1999).

Perhaps because females have weak hip extensors, which requires their use of the iliopsoas muscles for trunk control over the hips, they land from a jump in a more upright hip position, resulting in an altered knee angle on landing.[24] Decreased hip-muscle activation also decreases maximal possible quadriceps and hamstring activation. Moreover, because the stabilizing function of the monoarticular muscles (the glutei) facilitates the activation of the biarticular muscles (hamstrings and quadriceps), decreased hip-muscle activation reduces maximal possible quadriceps and hamstring activation.[25,27] This decreased activation alters optimal load-bearing capacity.[25,27] Females show a significantly shorter duration of gluteus medius activation in stance, or load-absorbing, phase when executing a cutting maneuver (W. B. Kibler, MD, unpublished data, 1999). This results in higher loads per unit of body weight in anteroposterior and varus/valgus directions in females. In addition, the peak loads are reached in a shorter time in females (W.B. Kibler, MD, unpublished data, 1999).

Further studies are needed to clarify the exact role these alterations play in ACL injury. However, strengthening programs that emphasize hip control—gluteal and hamstring activation in a closed-chain fashion—have been shown to be beneficial in injury prevention programs.[28]

Influence of Other Kinetic, Gravitational, and Muscle Forces

Frequently, patients who sustain noncontact ACL injuries will state that the injury occurred when they were decelerating (e.g., when changing directions or landing from a jump). These types of actions involve eccentric force generation by the quadriceps (i.e., the muscle is lengthening under tension) and slight knee flexion angles. Interestingly, the quadriceps exerts its maximum anterior shear force when knee flexion angles are small (10 to 30 degrees)(T. J. Noonan, MD, unpublished data, 1999). The activated quadriceps with the knee nearly in full extension places a measurable strain on the ACL. Eccentric activation of the quadriceps at high velocities provides even more force to strain the ACL, much more than is normally seen in a maximal isometric quadriceps contraction. In fact, integrated electromyographic studies demonstrate eccentric quadriceps muscle activation to be more than twofold greater than maximum voluntary contraction during such activities as running, cutting, and landing from a jump (R. A. Malinzak, MD, unpublished data, 1999). Valgus knee moments may further stress the ACL, whereas hamstring activation provides a posterior protective force to the ligament.[29,30] Biomechanical "perturbation" (i.e., a hit or jolt that makes the athlete unbalanced) or a sudden change in a planned activity further influences these voluntary movement patterns.

Examination of videotapes of noncontact ACL injuries frequently reveals that just prior to an injury athletes are slightly bumped or perform an awkward movement, from which they quickly recover by initiating a new movement pattern. For example, a basketball player begins her move to the basket, but suddenly another player causes her to quickly change her direction of movement and alter her already initiated movement pattern. With insufficient time to obtain information, the central nervous system tries to recover, and frequently the activity becomes more quadriceps-dominant as the player tries to regain balance. Unfortunately, this occurs at a time when the ACL is most susceptible to the shear forces of the quadriceps.

Women have been shown to perform cutting and landing maneuvers in a more erect posture than men, that is, with less hip and knee flexion. Theoretically, therefore, they should be at a greater risk for ACL injury than men when performing these activities (R. A. Malinzak, MD, unpublished data, 1999; L. J. Huston, MS, unpublished data, 1999). Moreover, the increase in knee valgus and greater quadriceps activation in women may further increase their risk for injury.[31]

Evaluation of ACL Injury Videotapes

To gain greater insight into the biomechanics of noncontact ACL injuries, videotapes have been analyzed. In one study in which 54 videotapes of ACL injuries occurring in basketball and soccer players were analyzed, 100% of the male basketball players were injured landing from a jump, whereas roughly half the women were injured landing from a jump, and half were injured when they stopped suddenly while running down the court (C. C. Teitz, MD, unpublished data, 1999). The center of gravity appeared to be behind the knee in two thirds of the injuries. Ground contact in the "flat foot" position was noted in two thirds of the injured female basketball players and in all injured male players. In soccer players, the flat-foot position was noted in two thirds of the athletes at the time of injury. Frequently, the lower-limb position noted at the time of injury was less than 30 degrees of knee flexion, knee valgus, and external rotation of the foot relative to the knee.

Making ground contact at the toes rather than in a flat-foot position makes it virtually impossible for the center of gravity to be behind the knee. Theoretically, when the center of gravity falls behind the knee, the rectus femoris, acting as a hip flexor, may be used to bring the trunk forward. This attempt may result in a powerful contraction of the rectus femoris, with a large anterior force being delivered to the tibia at the tubercle.

Therefore, from video analysis, it can be hypothesized that a neuromuscular training program to aid in the prevention of noncontact ACL injuries sustained in pivoting sports should include the following elements: a kinesthetic program to keep the center of gravity forward and the athlete on his or her toes (including strength and endurance training of the rectus abdominis, iliopsoas, and gastrocnemius-soleus muscles) and a program to encourage better lower-extremity rotational and angular control (including strength and endurance training of hip abductor and external rotator muscles).

Neuromuscular Prevention Programs

Several prevention programs based on altering biomechanical risk factors through neuromuscular training have been tried—all with impressive success. After a 10-year study of ACL injuries in female basketball players, Henning formulated a prevention program based on altering what he called the "quad-cruciate interaction"(N. D. Griffis, unpublished data, 1999). He believed that when the knee is straight during weight bearing, the ACL acts as a major restraint of forward movement of the tibia on the femur, providing an average of 86% of the total resistive force. With quadriceps contraction, the tibia moves forward, thus tightening and loading the ACL. When the knee is near full extension, anterior displacement of the tibia on the femur produced by a powerful quadriceps contraction could strain the ACL. If the quadriceps contracts when the knee is flexed 60 degrees or more, the anterior displacement of the tibia on the femur and, therefore, the ACL strain are less.

Henning concluded that the most common mechanisms of injury were planting and cutting (29%), straight-knee landing (28%), and one-step stop with the knee hyperextended (26%). Therefore, his program consisted of drills in which he had athletes practice substituting an accelerated rounded turn off a bent knee for the pivot and cut, landing on a bent knee instead of landing on a straight knee, and a three-step stop with the knee bent instead of one-step stop with the knee hyperextended—all techniques designed to decrease the quadriceps-cruciate interaction. Preliminary data from institution of his program in a limited population of Division I basketball players over a 2-year span demonstrated an 89% decrease in ACL injury rate (N. D. Griffis, unpublished data, 1999).

Henning's teaching tape consisted of examples of noncontact ACL injuries that occur in play situations, followed by illustrations of the recommended drills done in the gym as well as on the practice field. He believed that young athletes are the most receptive to technique modification and, therefore, encouraged teaching his "improved player technique skills" to children.

Caraffa et al[32] reasoned that since restoration of proprioceptive function is essential in ACL-injured and reconstructed knees, a prophylactically instituted program might decrease the occurrence of ACL injuries in an at-risk population. They developed a five-phase proprioceptive program based on increasingly difficult skills performed initially without a balance board and progressing through the use of a series of balance boards of various designs. Athletes participated in the program 20 minutes a day beginning 30 days before the beginning of the season. The incidence of ACL injuries in the 300 semi-professional and amateur soccer players who participated in their program was 0.15 injury per team per year over the 3 years surveyed, whereas the incidence of injury in 300 players of equally matched talent playing with similar equipment on similar fields was 1.15 ACL injuries per team per year ($P<0.001$). Criticisms of this study, however, are that subject selection was not randomized, and program standardization is difficult to assess. Therefore, although it has merit and is intriguing as a pilot study, confirmation by others appears reasonable before widespread use can be suggested.

Hewett et al[28] designed a three-part prevention program consisting of stretching, plyometrics (jumping drills), and strength training drills to address potential deficits in the neuromuscular strength and coordination of the stabilizing muscles about the knee joint (Table 1). They hypothesized that such deficits were the major factors contributing to ACL injury. This program has three phases, each approximately 2 weeks in duration: the technique phase (phase I), during which proper jumping techniques are taught (emphasizing correct posture and alignment, straight up-and-down jumps with no excessive side-to-side or forward-to-back movement, soft landings, and instant recoil);

Table 1
Sportsmetrics™ Training Program*

Exercise/Activity†	Duration/Repetitions	
Phase I (Technique):	Week 1:	Week 2:
1. Wall jumps	20 sec	25 sec
2. Tuck jumps‡	20 sec	25 sec
3. Broad jumps, stick land	5 reps	10 reps
4. Squat jumps‡	10 sec	15 sec
5. Double-leg cone jumps, side-to-side/back-to-front‡	30 sec/30 sec	30 sec/30 sec
6. 180 jumps	20 sec	25 sec
7. Bounding in place	20 sec	25 sec
Phase II (Fundamentals)	Week 3:	Week 4:
1. Wall jumps	30 sec	30 sec
2. Tuck jumps‡	30 sec	30 sec
4. Jump, jump, jump, vertical jump	5 reps	8 reps
5. Squat jumps‡	20 sec	20 sec
6. Bounding for distance	1 run	2 runs
7. Double-leg cone jumps, side-to-side/back-to-front‡	30 sec/30 sec	30 sec/30 sec
8. Scissor jump	30 sec	30 sec
9. Hop, hop, stick‡	5 reps/leg	5 reps/leg
Phase III (Performance):	Week 5:	Week 6:
1. Wall jumps	30 sec	30 sec
2. Step, jump up, down, vertical	5 reps	10 reps
3. Mattress jumps, side-to-side/back-to-front‡	30 sec/30 sec	30 sec/30 sec
4. Single-leg jumps for distance‡	5 reps/leg	5 reps/leg
5. Squat jumps‡	25 sec	25 sec
6. Jump into bounding‡	3 runs	4 runs
7. Single-leg hop, hop, stick	5 reps/leg	5 reps/leg

* Adapted with permission from Hewett TE, Stroupe AL, Nance TA, Noyes FR: Plyometric training in female athletes: Decreased impact forces increased hamstring torques. *Am J Sports Med* 1996;24:765-773.

† Prior to jumping exercises: stretching, 15-20 minutes; skipping, 2 laps; side shuffle, 2 laps. Each jumping exercise is followed by a 30-second rest period. Posttraining: cool-down walk, 2 minutes; stretching, 5 minutes.

‡ These jumps performed on mats.

the fundamentals phase (phase II), which concentrates on building strength, power, and agility; and the performance phase (phase III), which focuses on achieving maximum vertical jump height.

This program was found to decrease peak landing forces, decrease varus and valgus moments at the knee, increase hamstring power and strength, and increase hamstring-to-quadriceps peak torque ratio. In a trial involving 1,263 volleyball, soccer, and basketball athletes who participated in the program 3 days a week beginning 6 to 8 weeks before their season opened, untrained females had an incidence of knee injury 3.6 times higher than trained females; however, the rate of injury in trained females was the same as that in untrained males.

In a 26-year case-control study in northern Vermont, ACL sprains accounted for 2,006 of 15,550 (12.9%) of all ski injuries.[33] The risk of ACL injury in alpine skiing was found to be 2.2 times greater for females than for males, and ACL injuries increased from 4.5% of all injuries in 1972 to 19.3% in 1999. It was determined from a review of ACL injury tapes and data that the majority of ACL injuries in recreational skiing resulted from the "phantom foot" mechanism, which involves internal rotation of the tibia with the knee flexed well beyond 90 degrees (Fig. 3). Currently available ski-boot-binding systems do not "sense" the type of loading that results in this ACL injury and, therefore, are incapable of preventing injury in this situation.

The events that result in the phantom-foot mechanism include the following: (1) the skier is off balance to the rear; (2) the uphill arm is back; (3) the hips are below the knees (knees flexed beyond 90 degrees); (4) the uphill ski is unweighted; (5) the weight is on the inside edge of the downhill ski; (6) the upper body is generally facing the downhill ski. When all six elements of this profile are present at the same time, injury to the downhill leg is imminent.

The initial prevention program undertaken by the Vermont group during the 1993-1994 ski season was termed an "injury awareness program" and consisted of having participants (4,700 ski patrollers and instructors in 20 ski areas) analyze injury videos and develop strategies to avoid the events that result in injury.[34] The incidence of serious knee sprains was 62% lower in the "awareness-trained" group than in the control group of ski instructors and patrollers. Since then, the Vermont Ski Research Safety Group has created a teaching video available to the skiing public, which stresses the mechanism of ACL injury in skiing and addresses avoidance strategies. For example, if a skier senses that the elements of the phantom-foot mechanism are about to occur, an appropriate initial response is to keep the arms forward, the feet together, and the hands over both skis. Data on the effectiveness of the program in this study population are currently being analyzed.

Hunt Valley Consensus Conference on Prevention of Noncontact ACL Injuries

Recognizing a need to critically examine and summarize existing data on prevention strategies and their implied risk factors for noncontact ACL injuries, 22 orthopaedists, family physicians, biomechanists, and athletic trainers met in Hunt Valley, Md, in June 1999. Their goals were to increase awareness in the at-risk population and medical support personnel about prevention strategies and to stimulate increased efforts in injury prevention research. After carefully reviewing available data on injury risk factors and their associated prevention strategies, the participants formulated the following consensus statements:

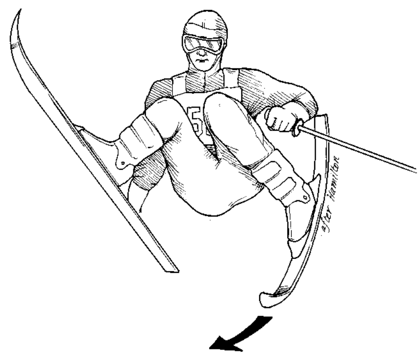

Figure 3 The "phantom foot" mechanism of injury in skiing. Note the internal rotation of the tibia with the knee flexed well beyond 90 degrees. (Adapted with permission from Vermont Safety Research: *ACL Awareness Training: Phase II.* Copyright 1994.)

Environmental Risk Factors

(1) At present there is no evidence that knee braces prevent ACL injuries.

(2) 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.

Anatomic Risk Factors

(1) There is much literature on the role of the femoral notch size and ACL injury, but because of the difficulty of obtaining valid and reliable measurements, no consensus on the role of the notch in ACL injury has been reached as yet.

(2) At present, there are insufficient data on ACL size (absolute or proportional) to support the concept that ligament size is related to the risk of injury.

(3) There are insufficient data to relate lower-extremity anatomic alignment to ACL injury; therefore, further research is needed.

Hormonal Risk Factors

(1) At present, there is no consensus in the scientific community that sex-specific hormones play a role in the increased incidence of ACL injury in female athletes, but further research in this area is encouraged.

(2) Hormonal intervention for ACL injury prevention cannot be justified.

(3) There is no evidence to recommend modification of activity or restriction from sport for females at any time during the menstrual cycle.

Biomechanical Risk Factors

(1) The knee is only one part of a kinetic chain; therefore, it must be borne in mind that anatomic sites other than the knee, including the trunk, hip, and ankle, may have a role in ACL injury.

(2) Common biomechanical factors involved in many injuries include impact on the foot rather than the toes during landing or changing directions, awkward dynamic body movements, and biomechanical perturbation prior to the injury.

(3) The common at-risk situation for noncontact ACL injuries appears to be deceleration, which occurs when the athlete cuts, changes direction, or lands from a jump.

(4) Neuromuscular factors are important contributors to the increased risk of ACL injuries in females and appear to be the most important reason for the differing ACL injury rates between males and females.

(5) Strong quadriceps activation during eccentric contraction was considered to be a major factor in injury to the ACL.

Prevention Strategies

After reviewing the existing neuromuscular training prevention programs, participants agreed on the following statements regarding prevention strategies:

(1) Early data show that specific training programs that enhance body control reduce ACL injury rates in female athletes and may increase athletic performance.

(2) Training and conditioning programs for male and female athletes in the same sport may need to be different.

(3) Those involved in the care of athletes should identify sport-specific at-risk motions and positions and encourage athletes to avoid these situations when possible.

(4) Strategies for activating protective neuromuscular responses when at-risk situations are encountered should be identified.

Future Research Directions

The consensus group emphasized the need to continue to define specific neuromuscular, proprioceptive, and motor control factors associated with injury. However, until specific predictive and protective factors are definitively identified, training and prevention programs should continue to be implemented, assessed, and improved. There is a pressing need to improve public and participant awareness of the risk of ACL injury and the possibilities for prevention.

Summary

The morbidity from ACL injuries in the young athletic population is of great concern. Furthermore, the economic impact of these injuries adds significantly to our rising medical costs. Therefore, efforts to prevent or at least decrease the rate of occurrence of these injuries seem prudent. Until recently, attempts to develop prevention programs centered on first clearly defining risk factors and injury mechanisms. Although these research efforts have yielded much information, they have not, with the exception of research efforts in downhill skiing, resulted in a clear understanding of the cause of noncontact ACL injuries.

It does appear, however, that neuromuscular control and balance as well as avoidance strategies for at-risk situations are critical factors for injury prevention. Prevention programs designed to increase neuromuscular control, improve balance, and teach avoidance strategies for at-risk situations appear to be effective in decreasing injury rates. Therefore, until research more clearly defines risk factors and injury mechanisms, it seems reasonable to increase awareness and encourage implementation of existing neuromuscular prevention programs, while continuing to closely monitor their results and improve their design as additional data become available.

References

1. Daniel DM, Fritschy D: Anterior cruciate ligament injuries, in DeLee JC, Drez D Jr (eds): *Orthopaedic Sports Medicine: Principles and Practice*. Philadelphia: WB Saunders, 1994, vol 2, pp 1313-1361.
2. Arendt E, Dick R: Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *Am J Sports Med* 1995;23:694-701.
3. Frank CB, Jackson DW: The science of reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am* 1997;79: 1556-1576.
4. Randall F, Miller H, Shurr D: The use of prophylactic knee orthoses at Iowa State University. *Orthot Prosthet* 1983;37:54-57.

5. Teitz CC, Hermanson BK, Kronmal RA, Diehr PH: Evaluation of the use of braces to prevent injury to the knee in collegiate football players. *J Bone Joint Surg Am* 1987;69:2-9.
6. Rovere GD, Haupt HA, Yates CS: Prophylactic knee bracing in college football. *Am J Sports Med* 1987;15:111-116.
7. Németh G, Lamontagne M, Tho KS, Eriksson E: Electromyographic activity in expert downhill skiers using functional knee braces after anterior cruciate ligament injuries. *Am J Sports Med* 1997;25:635-641.
8. Myklebust G, Maehlum S, Engebretsen L, Strand T, Solheim E: Registration of cruciate ligament injuries in Norwegian top level team handball: A prospective study covering two seasons. *Scand J Med Sci Sports* 1997;7:289-292.
9. Lambson RB, Barnhill BS, Higgins RW: Football cleat design and its effect on anterior cruciate ligament injuries: A three-year prospective study. *Am J Sports Med* 1996;24:155-159.
10. Scranton PE Jr, Whitesel JP, Powell JW, et al: A review of selected noncontact anterior cruciate ligament injuries in the National Football League. *Foot Ankle Int* 1997;18:772-776.
11. Rozzi SL, Lephart SM, Gear WS, Fu FH: Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *Am J Sports Med* 1999;27:312-319.
12. Nicholas JA: Injuries to knee ligaments: Relationship to looseness and tightness in football players. *JAMA* 1970;212:2236-2239.
13. Moretz JA, Walters R, Smith L: Flexibility as a predictor of knee injuries in college football players. *Phys Sportsmed* 1982;10:93-97.
14. Godshall RW: The predictability of athletic injuries: An eight-year study. *J Sports Med* 1975;3:50-54.
15. Steiner ME, Grana WA, Chillag K, Schelberg-Karnes E: The effect of exercise on anterior-posterior knee laxity. *Am J Sports Med* 1986;14:24-29.
16. Liu SH, Al-Shaikh R, Panossian V, et al: Primary immunolocalization of estrogen and progesterone target cells in the human anterior cruciate ligament. *J Orthop Res* 1996;14:526-533.
17. Slauterbeck JR, Narayan RS, Clevenger C, et al: Effects of estrogen level on the tensile properties of the rabbit anterior cruciate ligament (ACL). *Trans Orthop Res Soc* 1997;22:76.
18. Wojtys EM, Huston LJ, Lindenfeld TN, Hewett TE, Greenfield MLVH: Association between the menstrual cycle and anterior cruciate ligament injuries in female athletes. *Am J Sports Med* 1998;26:614-619.
19. Myklebust G, Maehlum S, Holm I, Bahr R: A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scand J Med Sci Sports* 1998;8:149-153.
20. Möller Nielsen J, Hammar M: Sports injuries and oral contraceptive use: Is there a relationship? *Sports Med* 1991;12:152-160.
21. Matthews PBC: Where does Sherrington's "muscular sense" originate? Muscles, joints, corollary discharges? *Annu Rev Neurosci* 1982;5:189-218.
22. Lephart S, Riemann B, Fu F: Introduction to the sensorimotor system, in Lephart SM, Fu FH (eds): *Proprioception and Neuromuscular Control in Joint Stability*. Champaign, Ill: Human Kinetics, 2000.
23. Ghez C: The cerebellum, in Kandel ER, Schwartz JH, Jessell TM (eds): *Principles of Neural Science*, 3rd ed. Norwalk, Conn: Appleton & Lange, 1991, pp 626-646.
24. Putnam CA: Sequential motions of body segments in striking and throwing skills: Descriptions and explanations. *J Biomech* 1993;26:125-135.
25. van Ingen Schenau GJ, Bobbert MF, Rozendal RH: The unique action of biarticular muscles in complex movements. *J Anat* 1987:155:1-5.
26. Gregoire L, Veeger HE, Huijing PA, van Ingen Schenau GJ: The role of mono-and biarticular muscles in explosive movements. *Int J Sports Med* 1984;5:301-305.
27. Bobbert MF, van Zandwijk JP: Dynamics of force and muscle stimulation in human vertical jumping. *Med Sci Sports Exerc* 1999;31:303-310.
28. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR: The effect of neuromuscular training on the incidence of knee injury in female athletes: A prospective study. *Am J Sports Med* 1999;27:699-706.
29. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GAM, Slauterbeck JL: Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res* 1995;13:930-935.
30. Draganich LF, Vahey JW: An in vitro study of anterior cruciate ligament strain induced by quadriceps and hamstrings forces. *J Orthop Res* 1990;8:57-63.
31. Huston LJ, Wojtys EM: Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med* 1996;24:427-436.
32. Caraffa A, Cerulli G, Projetti M, Aisa G, Rizzo A: Prevention of anterior cruciate ligament injuries in soccer: A prospective controlled study of proprioceptive training. *Knee Surg Sports Traumatol Arthrosc* 1996;4:19-21.
33. Natri A, Beynnon BD, Ettlinger CF, Johnson RJ, Shealy JE: Alpine ski bindings and injuries: Current findings. *Sports Med* 1999;28:35-48.
34. Ettlinger CF, Johnson RJ, Shealy JE: A method to help reduce the risk of serious knee sprains incurred in alpine skiing. *Am J Sports Med* 1995;23:531-537.