Adolescent female athletes who participate in sports that involve pivoting and jumping experience anterior cruciate ligament (ACL) injuries 4 to 6 times more often than adolescent male athletes participating in the same sports.1,2 The elevated risk of ACL injury, coupled with a geometric increase in female sports participation in the past 30 years, has led to a rise in ACL injuries in female athletes. (For more information about the statistical increase in injuries, see the Box, “Defining the problem of ACL injury incidence in female athletes,” on page 13.) Because of this increase in injury incidence, several studies have been done of both the mechanisms of injury and interventions to prevent injury.

Using tools to assess for neuromuscular deficits in young female athletes and then addressing identified deficits may help physicians in interventions with athletes who are in need of neuromuscular training. Targeted training applied to high-risk athletes may decrease ACL injury risk and help more female athletes enjoy the benefits of sports participation without the long-term disabilities associated with injury.

In this article, we summarize the investigations related to modifiable (biomechanical and neuromuscular) mechanisms that form the basis for the development of feasible interventions to lower ACL injury risk in high-risk female athletes. We also describe simple screening tools to help clinicians identify female athletes who are at high risk for this injury.

ABSTRACT: Anterior cruciate ligament (ACL) injuries often occur in adolescent athletes in sports that involve pivoting and jumping. Neuromuscular control deficits (ligament, quadriceps, and leg dominance) may contribute to a much higher incidence of ACL injury in females than in males. Methods for identifying these deficits during tasks related to ACL injury may help in the development of neuromuscular screening and training interventions. A protocol that was developed to reduce ACL injury risk improved sports-related performance. Physicians should assess pubertal and postpubertal female athletes to determine whether they display any neuromuscular deficits. If a patient is identified as being at risk, the physician should recommend neuromuscular training designed to ameliorate specific identified deficits. (J Musculoskel Med. 2006;23:12-38)

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ferences, female hormonal fluctuations, and neuromuscular control deficits in female athletes. A number of studies of ACL injury risk factors have focused on anthropometric and anatomic measures, such as thigh length and height and femoral notch width. However, static anatomic measures, such as quadriceps angle, often do not correlate with a dynamic injury mechanism or ACL injury risk, and these anatomic characteristics are nonmodifiable.

Hormonal factors, particularly those associated with fluctuations that occur during the follicular, ovulatory, and luteal phases of the menstrual cycle, also have been linked to ACL injury risk. However, the precise means by which they may contribute to injury risk and the extent to which they may be modified remain unclear.

The working hypothesis: Neuromuscular control deficits

Research geared to gaining understanding of modifiable risk factors has focused on the working hypothesis that ACL injury risk is related to measurable deficits in neuromuscular control (defined as muscle strength, power, or activation patterns that lead to increased knee joint load) in female athletes. It is hypothesized that female athletes demonstrate neuromuscular control deficits that increase lower extremity joint loads during sports activities and make important contributions to a higher incidence of knee injury. Risk factors include the following deficits: Ligament dominance, an imbalance between the neuromuscular and ligamentous control of dynamic knee joint stability, is demonstrated by an inability to control lower extremity coronal plane motion during landing and cutting. Quadriceps dominance is an imbalance between knee extensor and flexor strength, recruitment, and coordination. Leg dominance is an imbalance between the 2 lower extremities in strength and coordination. ACL injury probably occurs under conditions of high dynamic loading of the knee joint, when active muscular restraints do not adequately compensate for and dampen joint loads. Decreased neuromuscular control of the knee joint may place stress on the passive ligament structures that exceeds the failure strength of the ligament.

Neuromuscular control of high-load movements is required to maintain dynamic knee stability during landing and pivoting. Neur muscular control deficits that limit the effectiveness of the active neuromuscular control system to work synergistically with the passive joint restraints to create
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ate dynamic knee stability probably increases the risk of ACL injury. Methods for identifying neuromuscular control deficits during tasks related to actual ACL injury (eg, landing, cutting, and decelerating) may offer the greatest potential for development of neuromuscular screening interventions and application of them to targeting of high-injury-risk populations for neuromuscular training that is designed to correct observed deficits.24

Identifying neuromuscular control deficits during landing and cutting

Hewett and colleagues20 tested the hypothesis that poor or inadequate neuromuscular control of the lower limb biomechanics—in particular, the dynamic biomechanics of the knee joint during the execution of common but potentially hazardous sports movements—may contribute to high-risk mechanics used by female athletes. The study results demonstrated that peak landing forces are predicted by valgus torques at the knee in female athletes with significance; that female athletes use decreased hamstring activation when landing, compared with male athletes; and that female athletes have greater side-to-side differences in normalized hamstring peak torque and power.

Ford and coworkers12 obtained similar findings when they evaluated sex differences in the performance of a box drop vertical jump (Figure 1). They determined that female athletes land with a greater maximum valgus knee angle and greater total valgus knee motion than do male athletes. The female athletes had significant differences in maximum valgus knee angle between their dominant and nondominant sides. These differences in valgus measures (ligament dominance) and limb-to-limb asymmetries (leg dominance) reflect neuromuscular deficits that may indicate decreased dynamic knee joint control in female athletes.12

In follow-up to the assessment of high-risk landing positions, subsequent laboratory work focused on analysis of unanticipated, high-velocity, high-load cutting movements.21 The hypothesis was that female athletes would display increased lower extremity coronal plane motions in the absence of appropriate sagittal plane mechanics during the unanticipated...
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Cutting maneuver when compared with male athletes. The study results showed that female athletes exhibit greater knee abduction (valgus) angles than do male athletes. McLean and associates also found increased coronal plane measures at the knee when evaluating a similar sidestep cutting maneuver.

Findings of sex differences in knee and ankle kinematics in the frontal plane during cutting corroborate the findings of the landing studies. They further explain the sex differences in neuromuscular control during high-force, high-torque, and high-risk sports maneuvers.21

Manifestation of neuromuscular control deficits

Neuromuscular control deficits appear to be strongly related to an increased relative incidence of ACL injury in female athletes. In an extensive review of the literature, however, there was no apparent disparity in ACL injury risk between sexes before puberty.23,24

The next research question was, When during growth and development are neuromuscular control deficits and increased risk of ACL injury manifest? The biomechanics of growth and development show similar trends between the sexes before puberty; however, male and female neuromuscular patterns diverge significantly during and after puberty.25,26

During puberty, adolescents demonstrate a decline in coordination (continued on page 27)
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Correlations among height, weight, and neuromuscular performance observed in pubescent males are absent in pubescent females. For example, vertical jump height (a measure of whole-body power) increases steadily in males during puberty but not in females.26 In the absence of corresponding neuromuscular adaptation, musculoskeletal growth during puberty may facilitate the development of neuromuscular deficits, which may be displayed by decreased neuromuscular control of the knee joint.

If not addressed at the proper time, these deficits that accompany growth and development may...

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continue through adolescence into maturity. Mature female athletes demonstrate neuromuscular recruitment and leg strength imbalances well past their developmental years. These deficits may expose female athletes, especially elite athletes, to increased risk during years of intense athletic participation.

Dynamic knee joint control was evaluated in a large-scale 3-dimensional biomechanical study of 181 middle school and high school soccer and basketball players (101 females and 80 males). It was measured kinematically by medial knee motion and lower extremity valgus angle and kinetically by knee joint torques; comparison was made in females and males by maturational stage. Lower extremity bone length also was assessed.

Biomechanical and neuromuscular differences were not observed between male and female athletes before puberty. The pubertal female athletes landed with greater total lower extremity valgus motion and a greater maximum lower extremity valgus angle than did male athletes after the onset of maturation. The female athletes also demonstrated decreased flexor torques and significant differences between their dominant and nondominant sides in maximum lower extremity valgus angle between successive stages of maturation. The mature female athletes diverged significantly from the mature male athletes in all measures of neuromuscular control of the knee.

Therefore, it was concluded that growth during maturation is associated with decreased neuromuscular control of the knee. Decreased neuromuscular control of the knee was hypothesized to be responsible for the increased rates of ACL injury in female athletes compared with male athletes after the onset of pubertal growth.

Neuromuscular control deficits predict ACL injury

The next logical step was to determine whether measurable neuromuscular control deficits are actual predictors of ACL injury risk. A large-scale, prospective, 3-dimensional biomechanical cohort study was undertaken to determine whether prescreened female athletes who demonstrated decreased neuromuscular control and increased valgus joint loading would demonstrate an increased risk of ACL injury.

Before their competitive season, 205 female athletes in the high-risk sports of soccer, basketball, and volleyball were prospectively measured for neuromuscular control using 3-dimensional kinematics (joint angles) and joint loads using kinetics (joint moments) during a jump-landing task. Analy-
sis of variance and linear and logistic regression isolated predictors of risk in athletes who subsequently ruptured their ACL.

The 9 athletes who had a confirmed ACL rupture had significantly different knee kinematics and kinetics compared with the 196 athletes who did not have an ACL rupture. The mean knee abduction valgus angle at landing was 8° greater in the ACL-injured group than in uninjured athletes. ACL-injured athletes had a 2.5-times greater knee abduction moment and 20% higher ground reaction force; because their stance time was 16% shorter, increased motion, force, and moments occurred more quickly. The knee abduction moment predicted ACL injury status with 73% specificity and 78% sensitivity. The study results clearly demonstrate that female athletes who have increased dynamic valgus and high abduction loads are at increased risk for ACL injury.

Neuromuscular training to address neuromuscular deficits

Hewett and colleagues looked at the available literature and developed a research design to evaluate the effects of neuromuscular training on measures of lower extremity neuromuscular control. Peak landing forces and valgus torques at the knee were reduced significantly in female athletes after neuromuscular training.

Figure 7 – To improve hamstring strength, the single-leg pelvic bridge (A) and single-leg straight-leg dead lift (B) are performed on a training device without the addition of external weight.

Figure 8 – In the x-hops exercise, the athlete faces a quadrant pattern and stands on a single limb with her support knee slightly bent. She hops diagonally, lands in the opposite quadrant, maintains forward stance, and holds the deep knee flexion landing for 3 seconds. Then she hops laterally into the side quadrant and again holds the landing. Next, she hops diagonally backward and holds the landing. Finally, she hops laterally into the initial quadrant and holds the landing. She repeats this pattern for the required number of sets. The athlete should be encouraged to maintain balance during each landing, keeping her eyes up and her visual focus away from her feet.
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Myer and associates expanded this concept by evaluating the effects of a neuromuscular training protocol that was developed to reduce ACL injury risk and improve sports-related performance measures. This study incorporated plyometric jumping, dynamic resistance training, and postural control and balance training exercises into a comprehensive preseason training program that was implemented in a group of high-risk female athletes for 6 weeks. The protocol significantly reduced coronal plane measures that increase risk of injury and improved vertical jump, sprint speed, single-leg hop distance, and total body strength.

Protocols that incorporate similar techniques probably will decrease knee injury risk. In addition, the potential to improve performance probably will make neuromuscular training to prevent injury more appealing to coaches and athletes.

Managing athletic female patients: Practical recommendations

After the onset of puberty, female athletes may not have a “neuromuscular spurt” to match their rapid increase in growth and development. The lack of this enhanced neuromuscular adaptation may facilitate the development of neuromuscular deficits that increase the risk of ACL injury. Therefore, physicians should assess pubertal and postpubertal female athletes to determine whether they display any neuromuscular deficits (eg, ligament dominance, quadriceps dominance).
Ligament dominance may be tested with box drop vertical jump testing (Figure 1). Clinicians may visually assess the athlete’s tendency to allow her knees to move medially during landing and jumping; video camcorders help in this assessment. A female athlete who demonstrates excessive medial knee displacement when landing from a box drop vertical jump demonstrates ligament dominance and probably needs neuromuscular training to correct this technique (Figures 2, 3, 4, and 5).

Athletes are screened for indicators of quadriceps dominance with relatively common measurement techniques, such as isokinetic dynamometry (Figure 6) and, perhaps, even use of simple leg-curl and leg-extension weight machines. If the athlete exhibits a high level of quadriceps strength, a low level of hamstring strength, or a low hamstring-to-quadriceps ratio in 1 or both limbs, quadriceps dominance probably is present. Hamstring-to-quadriceps peak torque ratios of less than 0.55 may indicate increased injury risk. If hamstring-strength deficiencies are identified, clinicians should implement isolated hamstring strengthening exercises (Figure 7).

More sophisticated measurements of this imbalance may be attained through kinetic analysis of knee flexor-extensor torques during high-force sports movements. Extensor-to-flexor ratios greater than 2:1 may indicate that dynamic neuromuscular analysis training is required.

Leg dominance also may be assessed with use of a dynamometer or leg-curl and leg-extension machines. A difference in strength or power of 20% or more between limbs indicates a neuromuscular imbalance that may underlie significant injury risk. Another test that may be used to identify bilateral imbalances between limbs is a measure of the athlete’s ability to perform a single-leg balanced stance or a variety of hopping tasks (eg, for distance, timed, diagonal) with equal proficiency in both sides (Figures 8, 9, and 10). An athlete may have scores that show her to be at risk in 1, 2, or all 3 of these categories. That would warrant a physician recommendation of neuromuscular training designed to ameliorate specific identified deficits.
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