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Testing for neuromuscular deficits helps physicians determine interventions

Preventing ACL injuries in women

*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)*

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.

The mechanisms and risk factors

Most ACL injuries that female athletes experience in sports activity occur during a noncontact episode, typically during deceleration, lateral pivoting, or landing maneuvers that are often associated with high external knee-joint loads.[3,4] High knee-loading maneuvers occur during sports activity in both sexes; the mechanisms that underlie the greater incidence of ACL injury in female athletes are not completely defined.

Three major causative mechanisms are suggested to explain the disparity between sexes observed in ACL injury rates: anatomic dif-

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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[5] and height and femoral notch width.[6] However, static anatomic measures, such as quadriceps angle, often do not correlate with a dynamic injury mechanism or ACL injury risk,[7,8] 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.[9-11] However, the precise means by which they may contribute to injury risk and the extent to which they may be modified remain unclear.

Defining the problem of ACL injury incidence in female athletes

Since passage of Title IX of the Education Amendments of 1972, male participation in sports at the high school level has increased only from 3.7 million to 3.8 million. However, female participation has increased about 10-fold, approximately doubling every 10 years (from 0.3 million to 3.2 million).[35] This increase in high school sports participation in the past 30 years and a 5-fold increase in collegiate sports participation,[36] combined with an elevated risk of anterior cruciate ligament (ACL) injury in female athletes, has led to a rise in knee and ACL injuries. Consider the following:

- The National Collegiate Athletic Association has reported that about 150,000 women participate in varsity sports each year.[37] In a survey of member institutions, an average knee injury incidence of about 1 in every 10 female athletes was cited. Based on these figures, more than 15,000 debilitating knee injuries are expected to occur in female athletes at the varsity intercollegiate level during any given year.
- The total number of injuries is higher at the high school level.[35,38] The National Federation of State High School Associations has reported that about 3.2 million female athletes participate in high school sports programs.[35] About 1 in 50 to 70 female athletes at the high school level sustains a serious knee injury during any given year of varsity sports participation.[38,39] Participation in high school athletics probably contributes to more than 40,000 serious knee injuries in female athletes each year.
- At a conservative estimate of $17,000 per athlete, the cost of reconstructing and rehabilitating ACLs in these athletes would approach $700 million each year.[39]
- Other considerations include potential loss of entire seasons of sports participation and of scholarship funding, lowered academic performance,[40] long-term disability,[41] and a greater risk of radiographically diagnosed osteoarthritis in these athletes.[42]

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.[12-14] 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.[15]

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.[16] Decreased neuromuscular control of the knee joint may place stress on the passive ligament structures that exceeds the failure strength of the ligament.[17,18]

Neuromuscular control of high-load movements is required to maintain dynamic knee stability during landing and pivoting.[17,19] Neuromuscular control deficits that limit the effectiveness of the active neuromuscular control system to work synergistically with the passive joint restraints to cre-

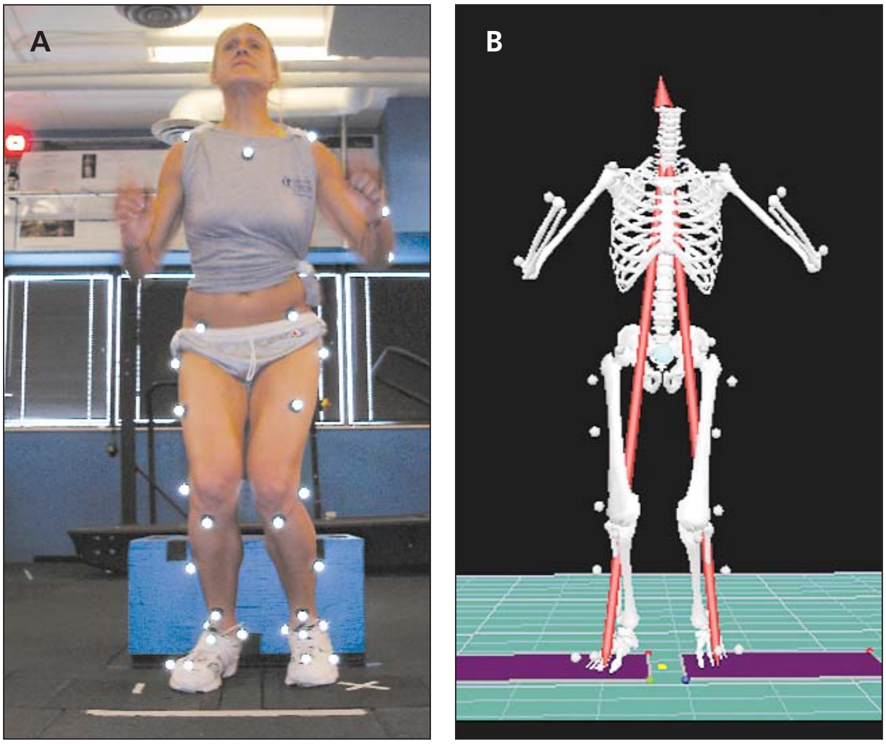

Figure 1 – *Three-dimensional motion analyses to assess female athletes performing the box drop vertical jump are depicted. The athlete is told to stand with her feet shoulder width apart on the box. She is instructed to drop (not jump) off the box. Once she contacts the ground, she should immediately redirect her center of mass into a maximum-effort vertical jump. In high-risk landing techniques, a female athlete shows visually evident medial knee motion (A). The skeletal representation shows the simultaneous landing recorded with 3-dimensional motion-analysis techniques (B). The increased ligament dominance alignment (medial knee collapse) is the result of ground reaction force vectors (shown in red) that cross lateral to the center of the knee joint. Female athletes who use this technique during a drop vertical jump landing demonstrate increased knee joint loads and have an increased risk of anterior cruciate ligament injury. Clinicians can visually assess ligament dominance in athletes with the use of a video camera to determine whether medial collapse occurs during the stance phase of the box drop vertical jump.*

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.[3,4]

Identifying neuromuscular control deficits during landing and cutting

Hewett and colleagues[20] 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 movement—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 coworkers[12] 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

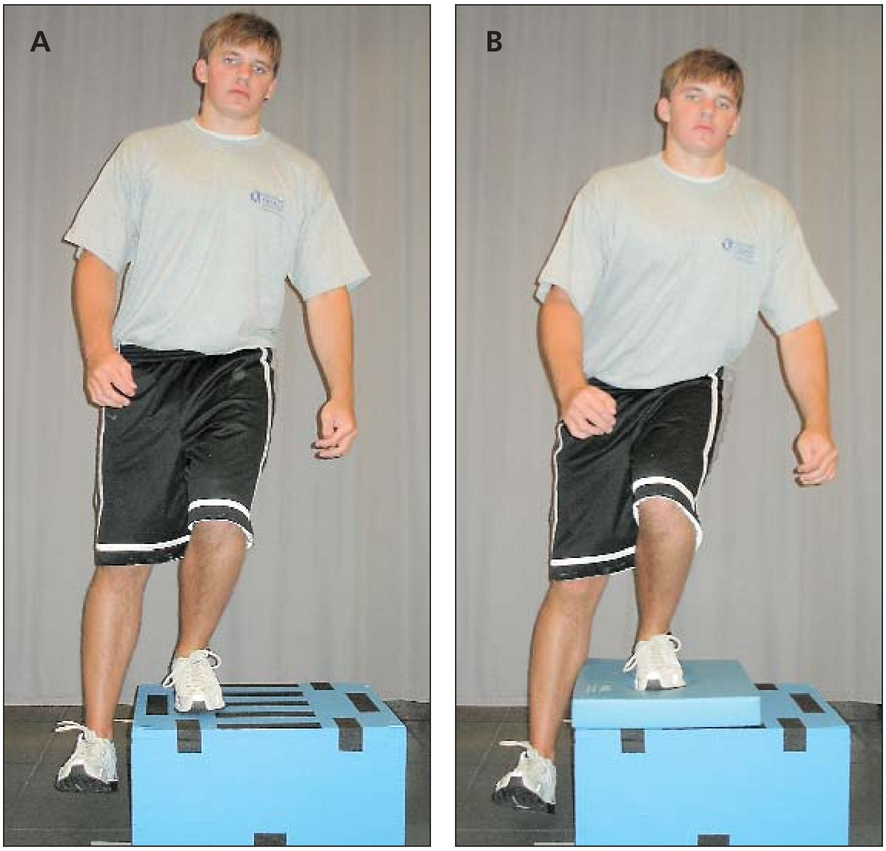

Figure 2 – *To improve active control of valgus knee collapse, the box heel touch exercise can be performed by stepping off a 12-inch box and touching the heel to the floor as shown (A). Clinicians should instruct the athlete to maintain neutral knee alignment while performing this maneuver. Difficulty is increased by placing a balance pad on the box top to decrease stability (B).*

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[22] 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 coordi-

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Figure 3 – *In this exercise, the athlete performs 3 successive broad jumps (as quickly as possible and attempting to reach maximum horizontal distance) and immediately progresses to a maximum-effort vertical jump. The third broad jump should be used as a preparatory jump that allows horizontal momentum to be quickly and efficiently transferred into vertical power. The athlete should be encouraged to provide minimal braking on the third broad jump to ensure that maximum energy is transferred to the vertical jump. On the fourth jump, coach the athlete to go directly vertical rather than horizontal and to use full arm extension to achieve maximum vertical height. Clinicians should provide the athlete with feedback about coronal plane knee alignment during all phases of this jump. (Figures 3, 4, 8, and 9 reproduced with permission of Myer GD, Ford KR, Hewett TE.* J Athl Train. *2004.[43])*

Figure 4 – *For the tuck jump exercise, the athlete starts in the "athletic position" (feet shoulder width apart) and initiates the jump with a slight crouch downward while she extends her arms behind her. She then swings her arms forward as she simultaneously jumps straight up and pulls her knees up as high as possible. At the highest point of the jump, the athlete's goal should be to bring her thighs parallel to the ground. On landing, she should immediately begin the next tuck jump. Encourage the athlete to land softly, using a toe to midfoot rocker landing. The athlete should not continue this jump if she cannot control the high landing force or if she uses a knock-kneed landing.*

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nation and balance,[27] as well as a distinct shift from risk of lower extremity fractures to increased probability of a ligament sprain.[28] However, males demonstrate power, strength, and coordination increases with chronologic age that correlate with maturational stage; females, on average, show little change throughout puberty.[25,26]

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.[26,29] In the absence of corresponding neuromuscular adaptation, musculoskeletal growth during puberty may facilitate the development of neuromuscular deficits,[30] 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

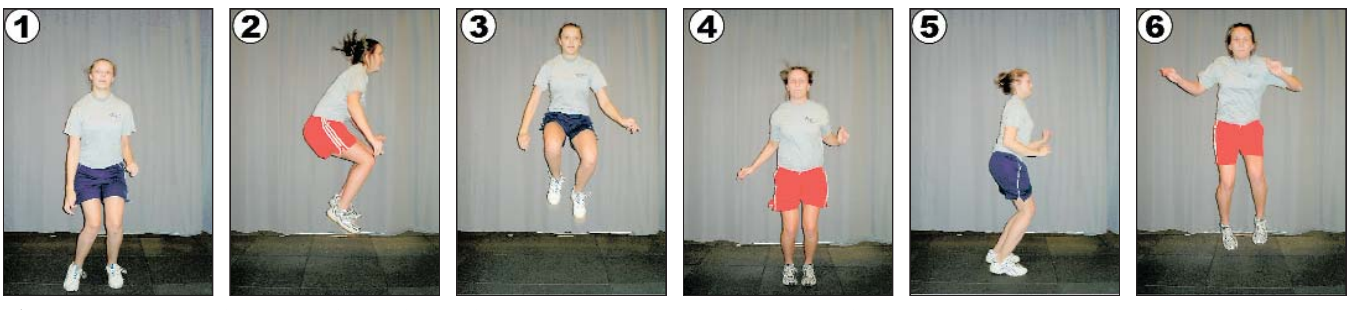

Figure 5 – *When athletes perform the tuck jump exercise, clinicians should try to correct 6 common errors. The athlete displays undesirable medial knee collapse (1), does not bring her knees to a parallel position at the top of flight (2), does not display synchronized lower limb positions during flight (3), lands with her feet too close together (4), lands in an undesirable staggered position (5), and does not land with both feet at the same time (6).*

continue through adolescence into maturity. Mature female athletes demonstrate neuromuscular recruitment and leg strength imbalances well past their developmental years.[31] 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).[32] 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 knee control. 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.[32]

Figure 6 – *Athletes may be screened for quadriceps dominance with simple leg-curl and leg-extension weight machines or isokinetic dynamometry. In the latter, the clinician's goal should be for the female athlete to demonstrate 90% limb-to-limb symmetry in quadriceps and hamstring strength when assessed at 300° per second. Hamstring strength also should be within two thirds of the values relative to quadriceps strength.*

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.[14]

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-

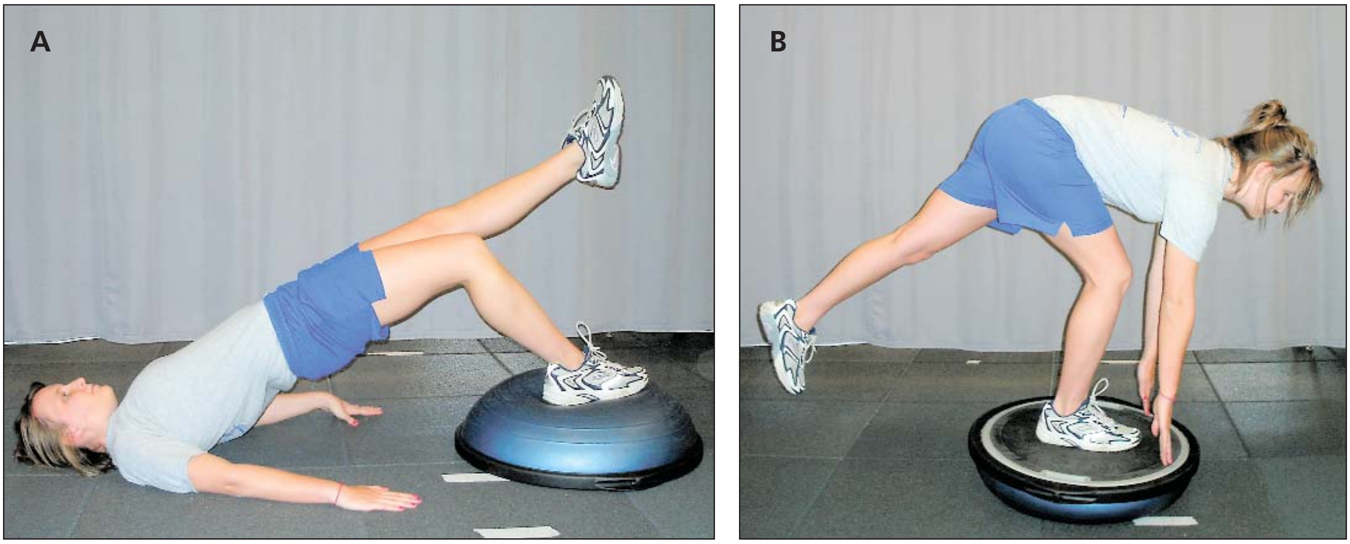

Figure 7 – *To improve hamstring strength, the single-leg pelvic bridge (A) and single-leg straight-leg dead lift (B) are performed on a training device without the addition of external weight.*

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[20] 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 af-

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.*

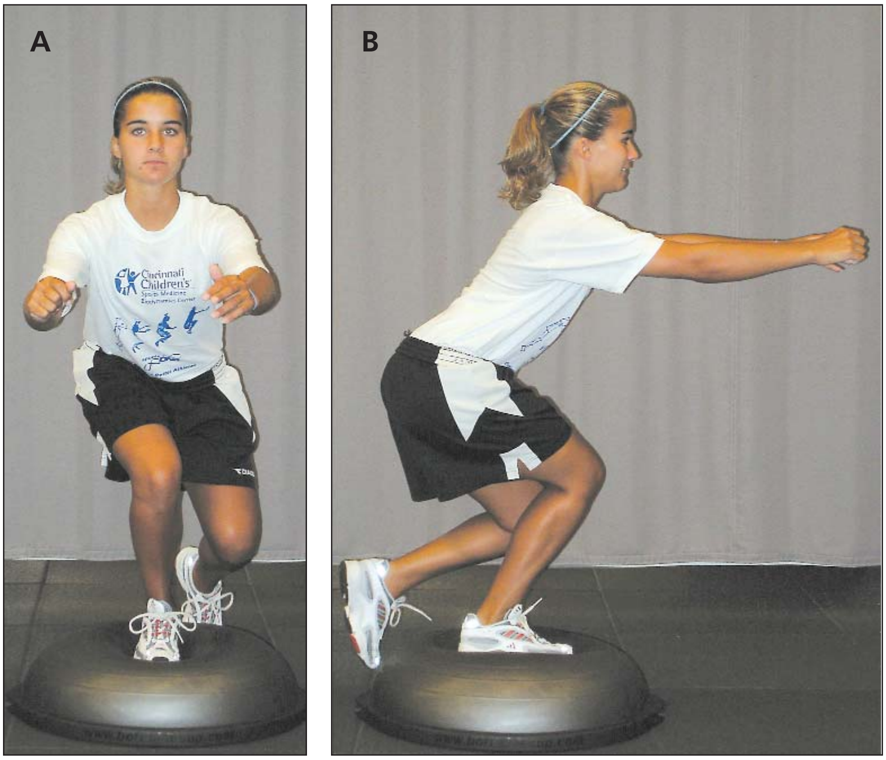

Figure 9 – *Athletes should perform balance drills on a balance device that has an unstable surface. The athlete begins on the device with a 2-legged stance and feet shoulder width apart, in the "athletic position" (A). As the athlete improves in performing the training drills, she can incorporate ball catches and single-leg balance drills. Encourage the athlete to maintain deep knee flexion when performing all drills (B).*

ter 6 weeks of neuromuscular training. Increased relative hamstring recruitment and normalized side-to-side differences in strength and power measures also were found. The study results also demonstrated potential for neuromuscular control deficits to be modified through neuromuscular training.

Myer and associates[33] 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.[33,34]

Practice Points

- Neuromuscular control deficits (ligament, quadriceps, and leg dominance) that limit dynamic knee stability probably increase the risk of anterior cruciate ligament (ACL) injury in female athletes.
- Assessment of sex differences in the performance of a box drop vertical jump and analysis of unanticipated, high-velocity, high-load cutting movements may help identify neuromuscular deficits.
- Training (eg, plyometric jumping and dynamic resistance exercises) may be used to modify neuromuscular control deficits, reduce ACL injury risk, and improve sports-related performance.

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, or leg 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. ■

Figure 10 – *Partner perturbation exercises are used to advance single-limb balance and postural control strategies and, especially, to correct side-to-side imbalances in postural control strategies.*

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References

1. 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.

2. Malone TR, Hardaker WT, Garrett WE, et al. Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *J South Orthop Assoc.* 1993;2:36-39.

3. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23:573-578.

4. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med.* 2004;32:1002-1012.

5. Beynnon B, Slauterbeck J, Padua D, et al. Update on ACL risk factors and prevention strategies in the female athlete. Paper presented at: National Athletic Trainers' Association 52nd Annual Meeting and Clinical Symposia; 2001; Los Angeles.

6. Scoville CR, Williams GN, Uhorchak JM, et al. Risk factors associated with anterior cruciate ligament injury. In: *Proceedings of the 68th Annual Meeting of the American Academy of Orthopaedic Surgeons.* Rosemont, Ill: American Academy of Orthopaedic Surgeons; 2001:564.

7. Endsley ML, Ford KR, Myer GD, et al. The effects of gender on dynamic knee stability and Q-angle in young athletes. Presented at: the Ohio Physical Therapy Association Fall Conerence; Columbus; 2003.

8. Myer GD, Ford KR, Hewett TE. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *J Electromyogr Kinesiol.* 2005;15:181-189.

9. Arendt EA, Bershadsky B, Agel J. Periodicity of noncontact anterior cruciate ligament injuries during the menstrual cycle. *J Gend Specif Med.* 2002;5:19-26.

10. Slauterbeck JR, Hardy DM. Sex hormones and knee ligament injuries in female athletes. *Am J Med Sci.* 2001;322:196-199.

11. Wojtys EM, Ashton-Miller JA, Huston LJ. A gender-related difference in the contribution of the knee musculature to sagittal-plane shear stiffness in subjects with similar knee laxity. *J Bone Joint Surg.* 2002;84A:10-16.

12. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* 2003;35:1745-1750.

13. Ford KR, Myer GD, Smith RL, et al. Use of an overhead goal alters vertical jump performance and biomechanics. *J Strength Cond Res.* 2005;19:394-399.

14. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* 2005;33:492-501.

15. Hewett TE, Myer GD, Ford KR. Prevention of anterior cruciate ligament injuries. *Curr Womens Health Rep.* 2001;1:218-224.

16. Beynnon BD, Fleming BC. Anterior cruciate ligament strain in-vivo: a review of previous work. *J Biomech.* 1998;31:519-525.

17. Li G, Rudy TW, Sakane M, et al. The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *J Biomech.* 1999;32:395-400.

18. Markolf KL, Graff-Radford A, Amstutz HC. In vivo knee stability: a quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg.* 1978;60A:664-674.

19. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc.* 2001;33:1168-1175.

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

21. Ford KR, Myer GD, Toms HE, Hewett TE. Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc.* 2005;37:124-129.

22. McLean SG, Lipfert SW, van den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc.* 2004;36:1008-1016.

23. Andrish JT. Anterior cruciate ligament injuries in the skeletally immature patient. *Am J Orthop.* 2001;30:103-110.

24. Buehler-Yund C. A longitudinal study of injury rates and risk factors in 5 to 12 year old soccer players. In: *Environmental Health*. Cincinnati: University of Cincinnati; 1999:161.

25. Beunen G, Malina RM. Growth and physical performance relative to the timing of the adolescent spurt. *Exerc Sport Sci Rev.* 1988;16:503-540.

26. Malina RM, Bouchard C. Timing and sequence of changes in growth, maturation, and performance during adolescence. In: Malina RM, Bouchard C, eds. *Growth, Maturation, and Physical Activity.* Champaign, Ill: Human Kinetics; 1991:267-272.

27. Harris SS. Readiness to participate in sports in care of the young athlete. In: Sullivan JA, Anderson SJ, eds. *Care of the Young Athlete.* Rosemont, Ill: American Academy of Orthopaedic Surgeons; 2000:19-24.

28. Adirim TA, Cheng TL. Overview of injuries in the young athlete. *Sports Med.* 2003;33:75-81.

29. Kellis E, Tsitskaris GK, Nikopoulou MD, Moiusikou KC. The evaluation of jumping ability of male and female basketball players according to their chronological age and major leagues. *J Strength Cond Res.* 1999;13:40-46.

30. Hewett TE, Paterno MV, Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop.* 2002;402:76-94.

31. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med.* 1996;24:427-436.

32. Hewett TE, Myer GD, Ford KR. Decrease in neuromuscular control about the knee with maturation in female athletes. *J Bone Joint Surg.* 2004;86A:1601-1608.

33. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res.* 2005;19:51-60.

34. Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among female athletes: a systematic review of neuromuscular training interventions. *J Knee Surg.* 2005;18:82-88.

35. High School Participation Survey. National Federation of State High School Associations. 2002: Indianapolis.

36. NCAA injury surveillance system summary. National Collegiate Athletic Association. 2002: Indianapolis.

37. Hutchinson MR, Ireland ML. Knee injuries in female athletes. *Sports Med.* 1995;19:288-302.

38. Chandy TA, Grana WA. Secondary school athletic injury in boys and girls: a three-year comparison. *Phys Sportsmed.* 1985;13:106-111.

39. 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.

40. Freedman KB, Glasgow MT, Glasgow SG, Bernstein J. Anterior cruciate ligament injury and reconstruction among university students. *Clin Orthop Relat Res*. 1998;356:208-212.

41. Ruiz AL, Kelly M, Nutton RW. Arthroscopic ACL reconstruction: a 5-9 year follow-up. *Knee.* 2002;9:197-200.

42. Myklebust G, Bahr R. Return to play guidelines after anterior cruciate ligament surgery. *Br J Sports Med.* 2005;39:127-131.

43. Myer GD, Ford KR, Hewett TE. Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *J Athl Train.* 2004;39:352-364.