Anterior Cruciate Ligament Injury Prevention in the Young Athlete: Evidence-Based Application

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ABSTRACT

SPORT PARTICIPATION AND EARLY SPECIALIZATION IS ON THE RISE, LEADING TO PEAK PERFORMANCE EXPECTATIONS AT A TIME OF MAJOR PHYSIOLOGICAL CHANGE. ANTERIOR CRUCIATE LIGAMENT INJURIES IN THE PEDIATRIC POPULATION WERE ONCE RARE, HOWEVER, ARE NOW SEEN WITH GREATER FREQUENCY. CHILDREN AS YOUNG AS 10 YEARS OF AGE DEMONSTRATE AT-RISK MOVEMENT PATTERNS ASSOCIATED WITH INJURY. BECAUSE LATE CHILDHOOD IS A CRITICAL PERIOD FOR REFINING MOVEMENT SKILLS, IT IS AN IDEAL TIME TO INTERVENE TO REDUCE INJURY RISKS. IDENTIFICATION OF RISK FACTORS, MASTERY OF FUNDAMENTAL SKILLS, AND STRENGTH TRAINING ARE VITAL FOR INJURY PREVENTION.

Sports participation is on the rise with approximately 35 million children aged 5–18 participating in organized sports in the United States (33). Children are training year-round and specializing in sport at earlier ages. Increased injury rates and changing injury patterns are paralleling this trend (48). Intrasubstance tears to the anterior cruciate ligament (ACL) in children were once rare, however, now are being seen with greater frequency (18,44–47,54,68,71).

Approximately 200,000 ACL injuries occur annually in the United States (33,64). About 1 in 20 female high school varsity athletes per year sustain a primary ACL injury (3,12,13,39). In a clinical series of pediatric patients aged 10–15 years with acute traumatic hemarthrosis of the knee, ACL injury was reported in 10–65% of such patients (18).

In addition to causing short-term disability, those who sustain an ACL rupture are at a high risk for developing knee osteoarthritis as early as 10 years after injury (7,39,50,51). In addition, studies have demonstrated a higher risk of subsequent reinjury after anterior cruciate ligament reconstruction (63). Injury may result in time loss from physical activity, lowered academic performance, and increased risk for psychosocial issues and may threaten general health maintenance efforts and contribute to obesity (26).

Consensus exists in the literature that gender differences in injury rates and neuromuscular risk factors appear to emerge with puberty and are most common among individuals 16 and 18 years of age (15,67,76). However, the frequency of ACL injury in young athletes has been increasing steadily around the ages of 10–12 (54,58,69,76). Currently, children as young as 10 years of age demonstrate movement patterns associated with injury risk (34,69,72). Movement patterns play a critical role in ACL injury because they influence anterior tibial shear force, which directly strains the ACL. Late childhood (age, 10–12 years) is a critical period for refining movement skills because of steady and gradual growth (27,28,30,41). Therefore, this may be an ideal time to intervene in movement modification during sport-specific tasks to reduce future injury risk.

Prevention is paramount to allow young athletes to safely receive the health benefits of recreational activity. Current literature displays no certainty as to whether this young age group responds to traditional ACL injury

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prevention programs that typically involve complex movement patterns that may be beyond their level of comprehension. However, given the success of prevention programs modifying neuromuscular risk factors in adolescents, it follows that intervening with children at a younger age may result in better long-term outcomes.

The purpose of this article is to review risk factors specific to children to efficiently work toward a preventive model that would reduce risk of ACL injury in young athletes.

RISK FACTORS SPECIFIC TO THE YOUNG ATHLETE

Early specialization, maturation, undeveloped physical skills, high-risk movement patterns, and an inadequate strength base all contribute to increased injury rates (33,34,37,43,49,66,70). Early specialization focuses on developing motor skills for a specific sport as opposed to developing overall fundamental motor skills.

Young athletes are vulnerable to injury secondary to growth-related factors such as growth spurts, maturity-associated variation, and immature or underdeveloped coordination and skills (8,10,52,66). These factors may exert their influence with more frequent and intensive training and competition seen today (16).

To successfully reduce the incidence of ACL injuries in young athletes, one must take a look at modifiable risk factors specific to this population.

PHYSICAL FITNESS DEFICITS

Fatigue, which is associated with inadequate physical fitness, has been correlated with injury risk (20,54). Youth with increased body mass index (BMI) were found to have a significantly higher risk of sustaining a sports-related injury than their normal-weight peers (55). A higher BMI may impact poor postural control affecting balance and coordination, poor physical fitness associated with muscle fatigue and subsequent injury, and low preparticipation physical activity levels associated with impaired neuromuscular and motor learning (55). Kidd et al. (43) documented that those who are unfit and perform "too much too soon" as well as athletically fit athletes who overexert themselves are at risk for injury. Thus, gradually increasing training load and improving flexibility, strength, and biomechanics according to age-appropriate guidelines is essential.

GROWTH SPURTS

The average age of onset for growth spurt is 10.5 years for girls and 12.5 years for boys (73). A young athlete's body changes as he/she grows, affecting bony levers and center of body mass, which impact postural alignment and neuromuscular control (37). During growth spurts, core strength, neuromuscular ability, coordination, and proprioception become imbalanced and contribute to injury risk (30,37).

Increasing demand of peak performance is expected at younger ages during a time of major physiological change (10). Care should be taken to ensure that demands such as expected sports-specific movement patterns or training loads placed on the athlete's body do not exceed their physiological capabilities. In addition, a child may master a skill before his/her growth spurt but may need to revisit that skill later on to refine the movement patterns secondary to the changes he/she incurs.

FUNDAMENTAL MOTOR SKILLS: MATURATION AND EFFECTS ON ALIGNMENT AND NEUROMUSCULAR CONTROL

Injury predisposition has been correlated to undeveloped physical skills (43,66) and is inevitable if a child lacks fundamental motor skills to meet the demands of the activity. Children do not master complex motor skills until late childhood (age, 10–12 years) and therefore are at risk when their age-appropriate skill set does not meet the demands imposed on them (1). Overuse injuries sustained by young athletes could be prevented if more emphasis was placed on the development of fundamental fitness skills, as opposed to sports-specific training (20).

PUBESCENT AND POSTPUBESCENT ATHLETES

Female athletes have a 2-fold to 8-fold greater ACL injury risk than male athletes (3,30–33,40). As a result, hundreds of studies have been published establishing risk factors and preventive measures for this at-risk population. Puberty has been associated with deficits, delays, and regressions of neuromuscular function, and many sex-related differences emerge that have been correlated with ACL rupture (11,12,25,37). Examples of modifiable risk factors include muscle strength and coordination, dynamic hip and knee control, lower extremity joint stiffness, and force attenuation during landing (13,21–25).

Adolescent females demonstrate measurable neuromuscular imbalances such as quadriceps dominance, ligament dominance, leg dominance, and trunk dominance, which have been associated with increased injury risk (17,25,37,39,40). Ligament dominance demonstrates tendency to stress the ligament before muscular activation to absorb ground reaction forces (GRFs). This may occur secondary to lack of dynamic muscular control, leading to increased valgus motion and high torque at the knee and ACL (Figure 1A and 1B). Quadriceps dominance results from preferential activation of knee extensors over knee flexors during sports-specific tasks. Ebben et al. (17) reported that women sustain quadriceps activation longer during cutting maneuvers and that their hamstring to quadriceps activation ratios were lower. Leg dominance pertains to imbalances in muscular strength and coordination of the limbs, which may place both limbs at risk. The weaker limb is compromised secondary to inability to dissipate forces; therefore, the stronger limb is subjected to high forces because of increased dependence and loading on that side (Figure 2A and 2B). Trunk dominance is caused by increased motion of the body's center of mass during single-leg landing, pivoting, or deceleration (17,37–39) (Figure 3A and 3B). Excessive trunk motion in the frontal plane

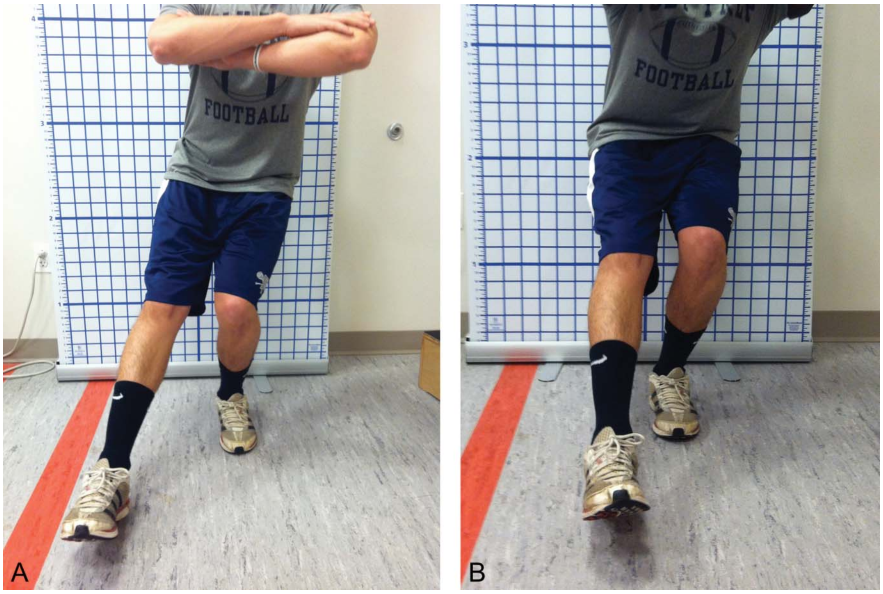

Figure 1. Ligament dominance: Differences in valgus knee motion during a single-leg squat. (A) Increased knee valgus motion in untrained athlete. (B) Proper knee alignment in trained athlete. Hips level and knee in neutral position.

and high GRFs and knee joint abduction load leaves the knee joint vulnerable to injury (37,39,40).

Males appear to have a neuromuscular spurt in strength, power, and coordination during puberty to adapt to increased bony lever arms and greater mass, whereas females show little change (39–41). However, before puberty, minimal gender differences have been demonstrated.

PREPUBESCENT

Even though minimal lower extremity biomechanical and neuromuscular differences in ACL ruptures have been observed before puberty, differences have been noted when comparing prepubescent and postpubescent subjects (8,15,36,37,44,52).

Children as young as 10 years demonstrated lower extremity neuromuscular movement patterns associated with injury risk during sport-related movements, such as landing and cutting (16,35,68). These movement patterns include reduced knee flexion, knee

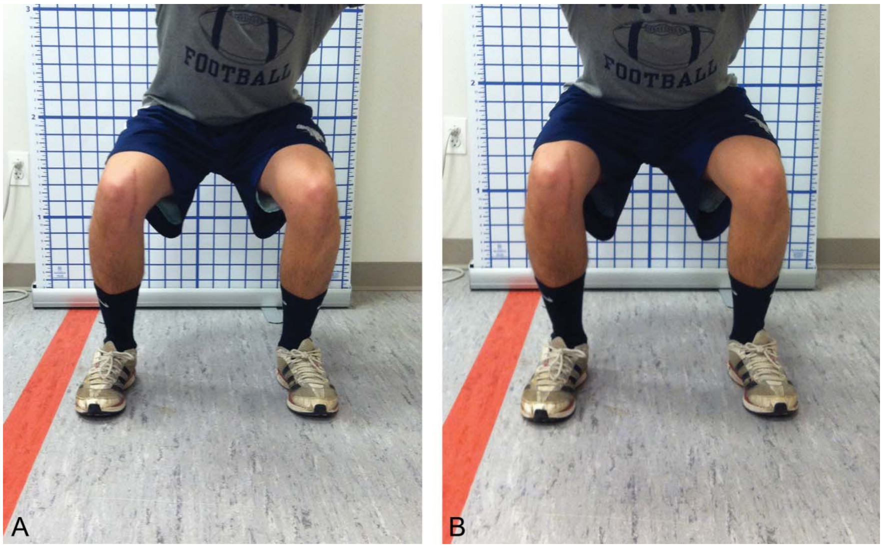

Figure 2. Leg dominance: (A) Weight shifted to left limb demonstrating increased loading and dependence. (B) Weight is evenly distributed between both limbs. Modified via verbal and visual cueing.

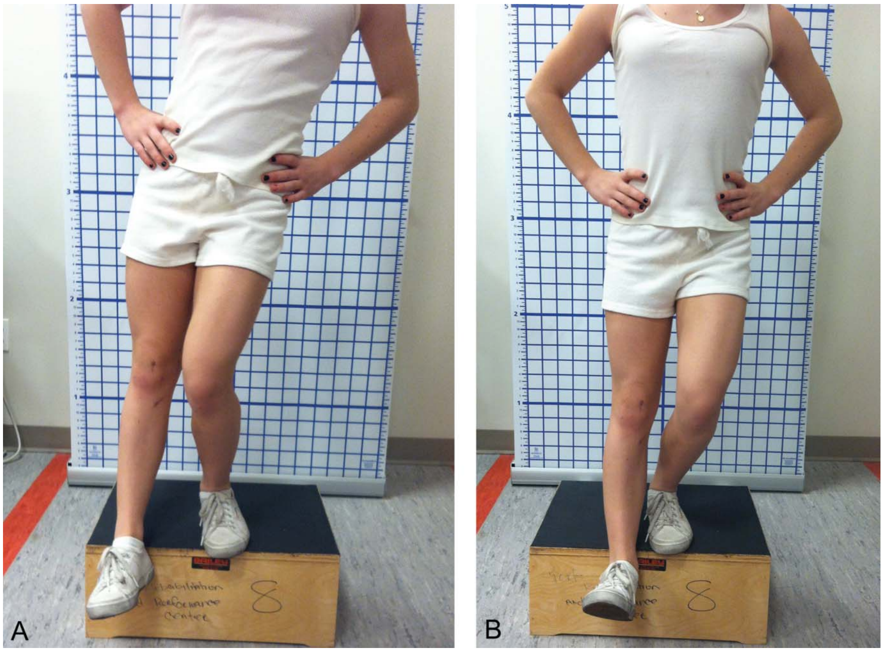

Figure 3. Trunk dominance: (A) Increased lateral displacement of the body's center of mass in an untrained athlete. (B) Balanced body's center of mass in a trained athlete.

valgus, and excessive leg rotation. Swartz et al. (72) demonstrated that a group of prepubescent children aged 7–11 years (boys and girls) exhibited greater GRFs and knee valgus and less hip and knee flexion at initial contact from a jump landing than the postpubescent subjects aged 19–29 years. The ability to modulate vertical GRFs upon impact and throughout landing may improve with aging, potentially because of various levels of contribution from physical maturation, skill development, and experience (72).

MODIFICATION OF RISK FACTORS FOR ANTERIOR CRUCIATE LIGAMENT INJURY PREVENTION IN YOUNG ATHLETES

Trends are changing and an increased number of ACL injuries are being seen at younger ages. Injury risk may be less during this stage of childhood; however, it may be an opportune time to intervene to modify risk factors and reduce further injury risk. The following section will discuss interventions and exercises that can be used with prepubescent children to effectively modify risk factors and therefore reduce future injury.

EFFECTS OF STRENGTH TRAINING: SPECIAL CONSIDERATIONS

Strength training programs have been shown to reduce the number and severity of knee injuries in adolescent athletes (6,35,56,57,74). Although these studies involve adolescents, it seems that strength training could provide similar protective effects to preadolescent children (20). There had been controversy in the past regarding safety of strength training for young children; however, it is proven safe and effective as long as supervision is provided and age-appropriate guidelines are followed (20).

It is important to note that skeletally immature children are prone to overuse injuries (19,29). Therefore, gradually increasing training loads and improving flexibility, strength, and motor skills according to age-appropriate guidelines is essential (20). Care should be taken to ensure demands or training loads do not exceed their physiological capabilities. It has been recommended that young athletes start with preparatory conditioning and instructional practice sessions versus competition (56).

GLUTEUS MEDIUS AND MAXIMUS STRENGTHENING FOR CORRECTION OF DYNAMIC VALGUS

Hewett et al. (37) showed that those who demonstrated knee valgus during jump landings were 2.5 times more likely to suffer ACL injury than those who did not. Gluteus maximus and medius play an increased role in preventing dynamic valgus collapse by controlling hip adduction and femoral rotation. Weakness has been identified as a predictor of injury secondary to inability of the weak muscles to keep the hip abducted during high single-leg activities such as landing and cutting (4,53,67). Studies have demonstrated improved control of dynamic valgus collapse of the knee with gluteus maximus and medius strengthening (53,61).

Electromyographic studies have reported that side-lying hip abduction, side planks, and lateral band walk have demonstrated sufficient maximal voluntary activation to allow strengthening of the gluteus medius (Figure 4A and 4B). Single-limb exercises such as single-limb squat may be used to activate gluteus medius more than double

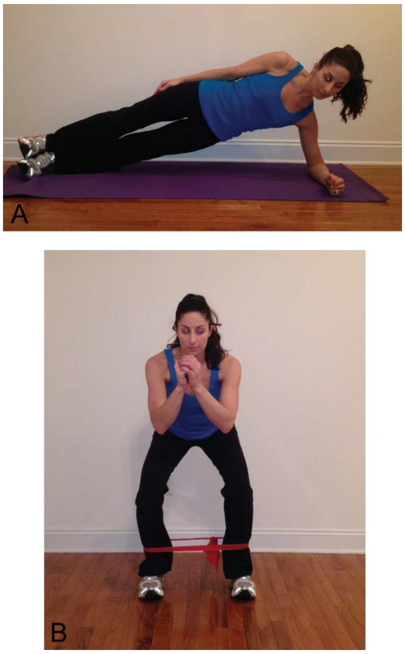

Figure 4. Gluteus strengthening for correction of dynamic valgus. (A) Side plank: strengthening of gluteus medius. (B) Lateral band walk: strengthening of gluteus medius.

stance exercises (48). Single-limb squats and single-leg deadlifts maximally elicited gluteus maximus (Figure 5A and 5B). It should be noted that one should not simply start with these exercises. These exercises are progressed to form double limb to single-limb stance once proper technique and safety is demonstrated.

ADDRESSING HAMSTRING STRENGTH FOR CORRECTION OF DYNAMIC VALGUS AND IMPROVED KNEE FLEXION WITH JUMP LANDINGS

Hamstring weakness and activation deficits play a role in controlling dynamic valgus postures by resisting anterior and lateral tibial translation and tibial rotations (2). Studies have demonstrated that weak hamstrings result in quadriceps dominance secondary to increased knee extensor moments over knee flexor moments during tasks that require increased lower extremity demand, therefore increasing risk (60). Adolescent girls exhibited less hamstring strength in comparison to age- and size-matched boys, confirming need for earlier intervention (59).

Hamstring activation is modifiable through strengthening and neuromuscular training (4,79). Studies have demonstrated improved dynamic valgus control and prelanding and landing activation with jump landings with neuromuscular training (79). Eccentric loading of the hamstrings, such as partnered Russian hamstring curls, has been found to be more effective in improving hamstring to quad ratio than traditional concentric exercises (42,59).

Agility training programs that have incorporated unanticipated directional changes have demonstrated improved medial hamstring activation during pivoting as well as a significant reduction in knee valgus loading during planned and unplanned conditions (13,75).

CORE STRENGTHENING FOR CORRECTION OF TRUNK DOMINANCE

Core weakness and proprioception have been associated with lateral trunk displacement, altered dynamic knee stability, and predicted knee injury risk (4,5,37,77–79). Effective programs should include core stability training, proprioceptive exercises, perturbations, and postural sway corrections. Core proprioceptive neuromuscular training has improved body sway; however, more research is needed secondary to the paucity in the literature on its effects on noncontact ACL rates.

CORRECTION OF LEG DOMINANCE AND LOWER EXTREMITY ALIGNMENT VIA CUEING

Leg dominance may be secondary to asymmetrical muscle weakness, flexibility, and/or pain avoidance. Training should focus on each leg in isolation if dominance is noted. If pain is reported,

Figure 5. (A) Single-leg squats: maximally elicits gluteus maximus. (B) Single-leg deadlift: maximally elicits gluteus maximus.

then the child should be referred to a physician for proper evaluation.

TECHNIQUE MONITORING AND FEEDBACK

Secondary to decreased attention span compared with adults, children should be actively monitored to ensure proper and safe technique. Mizner et al. (57) found that athletes were able to make significant positive changes in landing mechanics in repeat trials after brief verbal instruction. Padua and DiStefano (62) reported in a systematic review that verbal instruction and feedback for proper landing technique, auditory cues for minimizing landing forces, and performance under direct supervision on a regular basis significantly decreased vertical ground reaction forces. Studies that did not note change did not incorporate regular verbal or auditory feedback and did not provide direct supervision on a regular basis (79). Prapavessis and McNair (65) demonstrated a decrease in GRF with jumping via altered technique after only 1 feedback session.

ADDRESSING, FLEXIBILITY, PROPRIOCEPTIVE AND NEUROMUSCULAR DEFICITS DURING GROWTH SPURTS

During growth spurts, neuromuscular ability, coordination, and proprioception become imbalanced and contribute to risk of injury (37). Quadriceps and hamstring flexibility is critical to allow for sufficient knee and hip flexion during sports maneuvers to reduce ACL strain (37). In addition, proprioceptive training is vital to incorporate into one's program to allow children to improve within their new center of mass. Multiple studies demonstrated ACL injury reduction with use of balance and proprioceptive training as part of a multifaceted program with strengthening and neuromuscular training (9,37).

Recently, DiStefano et al. (15) demonstrated that athletes aged 9–11 years improved balance ability and vertical jump height after an injury prevention program that included core and lower extremity strengthening as well as balance activities including single leg ball toss and single-leg forward hopping.

MULTIFACETED PREVENTION PROGRAMS

Multifaceted programs that include strengthening, proprioception and neuromuscular training, plyometrics, and technique training have historically demonstrated the most success. However, limited research has been done with prepubescent children. Adapting a program specifically geared toward children may improve the ability to change neuromuscular risk factors for ACL injury and therefore reduce rate of injury entering into adolescence.

DiStefano et al. (14) assessed the effects of a Pediatric ACL Injury Prevention Program, specifically designed for children younger than 12 years. To maintain compliance, the program took approximately 12–14 minutes. It consisted of 3 phases over 9 weeks and gradually progressed core and lower extremity strength, flexibility via a dynamic warm-up, proprioception, plyometrics, and agilities. The first week placed emphasis on technique and reduced repetitions to allow mastery of tasks. Reduced knee external rotation at initial ground contact during cutting was demonstrated in the young athletes (14). Children require more feedback when learning a new task and therefore may benefit from a specialized program to meet their needs and to allow for success.

DISCUSSION

Historically, intervention strategies were focused on the adolescent athlete secondary to increased injuries incurred from 16 to 18 years of age. However, children between the ages of 10 and 12 years are demonstrating movement patterns associated with injury risk during sports-related movements (15) and injury rates are rising. Even though immediate injury risk may be less during this period, it serves as an ideal time to intervene and refine movement patterns to reduce future injury risk that tends to occur during adolescence (15).

The benefits of strength training, proprioceptive and neuromuscular training, flexibility, and plyometrics have been demonstrated in the literature to reduce injury rates in the adolescent athlete. In addition, it is evident that intervening at a young age is critical to the success in ACL injury prevention and may perhaps be the missing link. However, it is unclear whether this age group will respond to current adolescent ACL injury prevention programs that involve complex directions and may be beyond their level of comprehension and ability (14–16).

Children require more feedback when learning a new task and acquire new motor skills more efficiently when tasks are separated into basic components (15,16). Therefore, a program geared toward a young athlete's needs and skill set is highly recommended and would provide adequate intervention to possibly reduce the number of injuries incurred in childhood and possibly carried over into adolescence.

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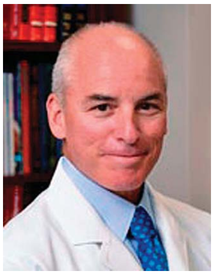

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REFERENCES

1. Adirim TA and Cheng TL. Overview of injuries in the young athlete. *Sports Med* 33: 75–81, 2003.
2. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lazaro-Haro C, and Cugat R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc* 17: 705–729, 2009.
3. Arendt E and Dick R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *Am J Sports Med* 23: 694–701, 1995.
4. Bien DP. Rationale and implementation of anterior cruciate ligament injury prevention warm-up programs in female athletes. *J Strength Cond Res* 25: 271–285, 2011.
5. Boden BP, Dean GS, Feagin JA Jr, and Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics* 23: 573–578, 2000.
6. Cahill B and Griffith E. Effect of preseason conditioning on the incidence and severity of high school football knee injuries. *Am J Sports Med* 6: 180–184, 1978.
7. Caine DJ and Golightly YM. Osteoarthritis as an outcome of paediatric sport: An epidemiological perspective. *Br J Sports Med* 45: 298–303, 2011.
8. Caine DJ and Maffulli N. Epidemiology of children's individual sports injuries. An important area of medicine and sport science research. *Med Sport Sci* 48: 1–7, 2005.
9. Caraffa A, Cerulli G, Projetti M, Aisa G, and Rizzo A. Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. *Knee Surg Sports Traumatol Arthrosc* 4: 19–21, 1996.
10. Carter CW and Micheli LJ. Training the child athlete: Physical fitness, health and injury. *Br J Sports Med* 45: 880–885, 2011.
11. Chandy TA and Grana WA. Secondary school athletic injury in boys and girls: A three-year comparison. *Phys Sportsmed* 13: 106–111, 1985.
12. Chaudhari AM, Lindenfeld TN, Andriacchi TP, Hewett TE, Riccobene JV, Myer GD, and Noyes FR. Knee and hip loading patterns at different phases in the menstrual cycle: Implications for the gender difference in anterior cruciate ligament injury rates. *Am J Sports Med* 35: 793–800, 2007.
13. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, and Munro BJ. Changing sidestep cutting technique reduces knee valgus loading. *Am J Sports Med* 37: 2194–2200, 2009.
14. DiStefano LJ, Blackburn TJ, Marshall SW, Guskiewicz KM, Garrett WE, and Padua DA. Effects of an age-specific anterior cruciate ligament injury prevention program on lower extremity biomechanics in children. *Am J Sports Med* 39: 949–957, 2011.
15. DiStefano LJ, Padua DA, Blackburn TJ, Garrett WE, Guskiewicz KM, and Marshall SW. Integrated injury prevention program improves balance and vertical jump height in children. *J Strength Cond Res* 24: 332–343, 2010.
16. DiStefano LJ, Padua DA, DiStefano MJ, and Marshall SW. Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. *Am J Sports Med* 37: 495–504, 2009.
17. Ebben WP, Fauth ML, Petushek EJ, Garceau LR, Hsu BE, Lutsch BN, and Feldmann CR. Gender-based analysis of hamstring and quadriceps muscle activation during jump landings and cutting. *J Strength Cond Res* 24: 408–415, 2010.
18. Eiskjaer S, Larsen ST, and Schmidt MB. The significance of hemarthrosis of the knee in children. *Arch Orthop Trauma Surg* 107: 96–98, 1988.
19. Emery CA. Risk factors for injury in child and adolescent sport: A systematic review of the literature. *Clin J Sport Med* 13: 256–268, 2003.
20. Faigenbaum AD. Strength training for children and adolescents. *Clin Sports Med* 19: 593–619, 2000.
21. Ford KR, Myer GD, and Hewett TE. Longitudinal effects of maturation on lower extremity joint stiffness in adolescent athletes. *Am J Sports Med* 38: 1829–1837, 2010.
22. Ford KR, Myer GD, and Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc* 35: 1745–1750, 2003.
23. Ford KR, Myer GD, Smith RL, Vianello RM, Seiwert SL, and Hewett TE. A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. *Clin Biomech (Bristol, Avon)* 21: 33–40, 2006.
24. Ford KR, Myer GD, Toms HE, and Hewett TE. Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc* 37: 124–129, 2005.
25. Ford KR, Shapiro R, Myer GD, Van Den Bogert AJ, and Hewett TE. Longitudinal sex differences during landing in knee abduction in young athletes. *Med Sci Sports Exerc* 42: 1923–1931, 2010.
26. Freedman KB, Glasgow MT, Glasgow SG, and Bernstein J. Anterior cruciate ligament injury and reconstruction among university students. *Clin Orthop Relat Res* 356: 208–212, 1998.
27. Gabbard CP. *Lifelong Motor Development* (5th ed). San Francisco, CA: Pearson Benjamin Cummings, 2008.
28. Gallahue DL. *Development Physical Education for Today's Children* (3rd ed). Madison, WI: Brown & Benchmark Publishers, 1996.
29. Gallahue DL and Ozmun JC. *Understanding Motor Development: Infants, Children, Adolescents, Adults* (6th ed). New York, NY: McGraw-Hill, 2006.
30. Gianotti SM, Marshall SW, Hume PA, and Bunt L. Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. *J Sci Med Sport* 12: 622–627, 2009.
31. Giugliano DN and Solomon JL. ACL tears in female athletes. *Phys Med Rehabil Clin N Am* 18: 417–438, 2007.
32. Gomez E, DeLee JC, and Farney WC. Incidence of injury in Texas girls' high school basketball. *Am J Sports Med* 24: 684–687, 1996.
33. Grunbaum JA, Kann L, Kinchen SA, Williams B, Ross JG, Lowry R, and Lloyd K. Youth risk behavior surveillance—United States (Abridged). *J Sch Health* 74: 307–324, 2000.
34. Hass CJ, Schick EA, Tillman MD, Chow JW, Brunt D, and Cauraugh JH. Knee biomechanics during landings:

Comparison of pre- and postpubescent females. *Med Sci Sports Exerc* 37: 100–107, 2005.

35. Henja WF, Rosenberg A, Buturusis DJ, and Krieger A. The prevention of sports injuries in high school students through strength training. *Natl Strength Cond Assoc J* 4: 28–31, 1982.
36. Hewett TE and Johnson DL. ACL prevention programs: Fact or fiction? *Orthopedics* 33: 36–39, 2010.
37. Hewett TE, Myer GD, Ford KR, Paterno MW, and Quatman CE. The 2012 ABJS Nicolas Andry Award: The sequence of prevention: A systematic approach to prevent anterior cruciate ligament injury. *Clin Orthop Relat Res* 470: 2930–2940, 2012.
38. Hewett TE, Paterno MV, and Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop Relat Res* 402: 76–94, 2002.
39. Hewett TE, Stroupe AL, Nance TA, and Noyes FR. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am J Sports Med* 24: 765–773, 1996.
40. Hewett TE, Stroupe AL, Nance TA, and Noyes FR. Plyometric training in female athletes: Decreased impact forces and increased hamstring torques. *Am J Sports Med* 24: 765–773, 1996.
41. Jurimae T and Jurimae J. *Growth, Physical Activity, and Motor Development in Prepubertal Children*. Boca Raton, FL: CRC Press LLC, 2000.
42. Kaminski TW, Wabbersen CV, and Murphy RM. Concentric versus enhanced eccentric hamstring strength training: Clinical implications. *J Athl Train* 33: 216–221, 1998.
43. Kidd PS, McCoy C, and Steenbergen L. Repetitive strain injuries in youth. *J Am Acad Nurse Pract* 12: 413–426, 2000.
44. Kloeppel-Wirth S, Koltai JL, and Dittmer H. Significance of arthroscopy in children with knee joint injuries. *Eur J Pediatr Surg* 2: 169–172, 1992.
45. Kocher MS, Foreman ES, and Micheli LJ. Laxity and functional outcome after arthroscopic reduction and internal fixation of displaced tibial spine fractures in children. *Arthroscopy* 19: 1085–1090, 2003.
46. Kocher MS, Mandiga R, Klingele K, Bley L, and Micheli LJ. Anterior cruciate ligament injury versus tibial spine fracture in the skeletally immature knee: a comparison of skeletal maturation and notch width index. *J Pediatr Orthop* 24: 185–188, 2004.
47. Kocher MS, Micheli LJ, Gerbino P, and Hresko MT. Tibial eminence fractures in children: Prevalence of meniscal entrapment. *Am J Sports Med* 31: 404–407, 2003.
48. Krause DA, Jacobs RS, Pilger KE, Sather BR, Sibunka SP, and Hollman JH. Electromyographic analysis of the gluteus medius in five weight bearing exercises. *J Strength Cond Res* 23: 2689–2694, 2009.
49. Ladenhauf HN, Graziano J, and Marx RG. Anterior cruciate ligament prevention strategies: Are they effective in treating young athletes? Current concepts and review of the literature. *Curr Opin Pediatr* 25: 65–71, 2012.
50. Lohmander LS, Englund PM, Dahl LL, and Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: Osteoarthritis. *Am J Sports Med* 35: 1756–1769, 2007.
51. Lohmander LS, Ostenberg A, Englund M, and Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum* 50: 3145–3152, 2004.
52. Malina RM and Bouchard C. *Timing and Sequence of Changes in Growth, Maturation, and Performance During Adolescence. Growth, Maturation, and Physical Activity*. Champaign, IL: Human Kinetics, 1991. pp. 267–272.
53. Mascal CL, Landel R, and Powers C. Management of patellofemoral pain targeting hip, pelvis, and trunk muscle function: 2 case reports. *J Orthop Sports Phys Ther* 33: 647–674, 1978.
54. McCarthy MM, Graziano J, Green DW, and Cordasco FA. All-epiphyseal, all-inside anterior cruciate ligament reconstruction technique for skeletally immature patients. *Arthrosc Tech* 1: 231–239, 2012.
55. McHugh MP. Oversized young athletes: A weight concern. *Br J Sports Med* 44: 45–49, 2010.
56. Micheli L. Sports training and the young athlete: How much is enough? *Sidelines* 8: 1–4, 1999.
57. Mizner RL, Kawaguchi JK, and Chmielewski TL. Muscle strength in the lower extremity does not predict post-instruction improvements in the landing patterns of female athletes. *J Orthop Sports Phys Ther* 38: 353–361, 2008.
58. Mizuta H, Kubota K, Shiraishi M, Otsuka Y, Nagamoto N, and Takagi K. The conservative treatment of complete tears of the anterior cruciate ligament in skeletally immature patients. *J Bone Joint Surg Br* 77: 890–894, 1995.
59. Mjolsnes R, Arnason A, Osthagen T, Raastad T, and Bahr RA. 10 week randomized trial comparing eccentric vs concentric hamstring strength training in well-trained soccer players. *Scand J Med Sci Sports* 14: 311–317, 2004.
60. Myer GD, Ford KR, Divine JG, Wall EJ, Kahanov L, and Hewett TE. Longitudinal assessment of noncontact anterior cruciate ligament injury risk factors during maturation in a female athlete: A case report. *J Athl Train* 44: 101–109, 2009.
61. Myer GD, Ford KR, and Hewett TE. Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *J Athl Train* 39: 352–364, 2004.
62. Padua DA and DiStefano LJ. Sagittal plane knee biomechanics and vertical ground reaction forces are modified following ACL injury prevention programs: A systematic review. *Sports Health* 1: 165–173, 2009.
63. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, and Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med* 22: 116–121, 2012.
64. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Huang B, and Hewett TE. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med* 38: 1968–1978, 2010.
65. Prapavessis H and McNair PJ. Effects of instruction in jumping technique and experience jumping on ground reaction forces. *J Orthop Sports Phys Ther* 33: 2004–2207, 2003.
66. Purvis JM and Burke RG. Recreational injuries in children: Incidence and prevention. *J Am Acad Orthop Surg* 9: 365–374, 2001.
67. Quatman CE, Ford KR, Myer GD, and Hewett TE. Maturation leads to gender differences in landing force and vertical jump performance: A longitudinal study. *Am J Sports Med* 34: 806–813, 2006.
68. Schub D and Saluan P. Anterior cruciate ligament injuries in the young athlete: evaluation and treatment. *Sports Med Arthrosc Rev* 19: 34–43, 2011.
69. Shea KG, Pfeiffer R, Wang JH, Curtin M, and Apel PJ. Anterior cruciate ligament injury in pediatric and adolescent soccer players: An analysis of insurance

data. *J Pediatr Orthop* 24: 623–628, 2004.

70. Smith A, Andrish J, and Micheli L: The prevention of sports injuries of children and adolescents. *Med Sci Sports Exerc* 25: 1–7, 1993.

71. *Sporting Goods Manufacturers Association Sports Market Research. US Trends in Team Sports*. Washington, DC: 2009.

72. Swartz EE, Decoster LC, Russell PJ, and Croce RV. Effects of developmental stage and sex on lower extremity kinematics and vertical ground reaction forces during landing. *J Athl Train* 40: 9–14, 2005.

73. Tanner J. Human growth: A comprehensive treatise. In: *Postnatal Growth Neurobiology* (2nd ed). Falkner F and Tanner J, eds. New York, NY: Plenum Press, 1986.

74. Unge A, Rosch D, Peterson L, Baumann TG, and Dvorak J. Prevention of soccer injuries: A prospective intervention study in youth amateur players. *Am J Sports Med* 30: 652–659, 2001.

75. Wilderman DR, Ross SE, and Padua DA. Thigh muscle activity, knee motion, and impact force during side-step pivoting in agility-trained female basketball players. *J Athl Train* 44: 14–25, 2009.

76. Yu B, McClure SB, Onate JA, Guskiewicz KM, Kirdkendall DT, and Garrett WE. Age and gender effects on lower extremity kinematics of youth soccer players in a stop-ump task. *Am J Sports Med* 33: 1356–1365, 2005.

77. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, and Cholewicki J. The effects of core proprioception on knee injury: A prospective biomechanical-epidemiologic study. *Am J Sports Med* 35: 368–373, 2007.

78. Zazulak BT, Ponce PL, Straub SJ, Medvecky MJ, Avedisian L, and Hewett TE. Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther* 35: 292–299, 2005.

79. Zebis MK, Bencke J, Anderson LL, Dossing S, Alkjaer T, Magnusson SP, Kjaer M, and Aagaard P. The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. *Clin J Sport Med* 18: 329–337, 2008.