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Cynthia R. LaBella, William Hennrikus, Timothy E. Hewett and COUNCIL ON SPORTS MEDICINE AND FITNESS, and SECTION ON ORTHOPAEDICS

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## CLINICAL REPORT

# Anterior Cruciate Ligament Injuries: Diagnosis, Treatment, and Prevention

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**KEY WORDS**

knee injuries, athletes, sports, adolescents

**ABBREVIATIONS**

ACL—anterior cruciate ligament

CI—confidence interval

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## abstract

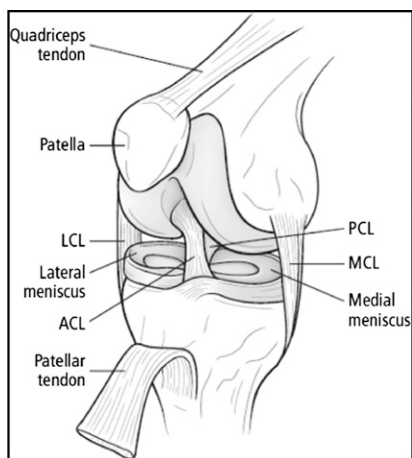
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The number of anterior cruciate ligament (ACL) injuries reported in athletes younger than 18 years has increased over the past 2 decades. Reasons for the increasing ACL injury rate include the growing number of children and adolescents participating in organized sports, intensive sports training at an earlier age, and greater rate of diagnosis because of increased awareness and greater use of advanced medical imaging. ACL injury rates are low in young children and increase sharply during puberty, especially for girls, who have higher rates of noncontact ACL injuries than boys do in similar sports. Intrinsic risk factors for ACL injury include higher BMI, subtalar joint overpronation, generalized ligamentous laxity, and decreased neuromuscular control of knee motion. ACL injuries often require surgery and/or many months of rehabilitation and substantial time lost from school and sports participation. Unfortunately, regardless of treatment, athletes with ACL injuries are up to 10 times more likely to develop degenerative arthritis of the knee. Safe and effective surgical techniques for children and adolescents continue to evolve. Neuromuscular training can reduce risk of ACL injury in adolescent girls. This report outlines the current state of knowledge on epidemiology, diagnosis, treatment, and prevention of ACL injuries in children and adolescents. *Pediatrics* 2014;133:e1437–e1450

## INTRODUCTION

Anterior cruciate ligament (ACL) injuries are a serious concern for physically active children and adolescents. The ACL is 1 of the 4 major ligaments that stabilize the knee joint (Fig 1). Its main function is to prevent the tibia from sliding forward relative to the femur. The ACL also assists with preventing excessive knee extension, knee varus and valgus movements, and tibial rotation.<sup>1,2</sup> An intact ACL protects the menisci from shearing forces that occur during athletic maneuvers, such as landing from a jump, pivoting, or decelerating from a run.

Physicians caring for young athletes have noted an increase in the numbers of ACL injuries over the past 2 decades.<sup>3,4</sup> Reasons for the increase in ACL injury rate include the growing number of children and adolescents participating in organized sports, increased participation in high-demand sports at an earlier age, and a greater rate of diagnosis as a result of increased awareness that ACL injuries can occur in skeletally immature patients and more frequent use of advanced medical imaging.<sup>4–8</sup>



**FIGURE 1**

Anatomic structures of the knee. LCL, lateral collateral ligament; MCL, medial collateral ligament; PCL, posterior cruciate ligament. (Reproduced with permission from Harris SS, Anderson SJ, eds. *Care of the Young Athlete*. 2nd ed. Elk Grove Village, IL: American Academy of Pediatrics and American Academy of Orthopedic Surgeons; 2009:410.)

## EPIDEMIOLOGY OF ACL INJURY

The incidence of ACL injuries in the general population can be estimated from national registries, which were established in Norway (2004), Denmark (2005), and Sweden (2006) to monitor the outcomes of ACL reconstruction surgery. Between 2006 and 2009, all Norwegian hospitals participated in the registry, with a total compliance of 97%. In the 10- to 19-year age group, the annual incidence of primary ACL reconstructions was 76 per 100 000 girls and 47 per 100 000 boys.<sup>9</sup> This number underestimates the true incidence of ACL injuries, however, because it does not include those treated nonoperatively.

Most ACL injuries are sports-related; therefore, injury rates are higher in athletes. The National Collegiate Athletic Association Injury Surveillance System has compiled data for 16 sports (8 men's and 8 women's) over 16 years from a sample of colleges and universities (approximately 15%).<sup>2</sup> ACL injury rates were highest in men's spring football and women's gymnastics (33

per 100 000 athlete-exposures) (Fig 2). In women's sports, ACL injury rates represented a larger proportion of total injuries than in men's sports (3.1% vs 1.9%), with women's basketball and women's gymnastics topping the list at 4.9% of total injuries.<sup>10</sup>

Overall, high school athletes have lower rates of ACL injuries than do collegiate athletes (5.5 vs 15 per 100 000 athlete-exposures) but a similar injury distribution across sports.<sup>2,11</sup> Since 2005, the National High School Sports-Related Injury Surveillance Study has compiled data on the incidence of ACL injuries in 18 sports.<sup>11</sup> From 2007 to 2012, ACL injury rates were highest in girls' soccer and boys' football (11.7 and 11.4 per 100 000 athlete-exposures, respectively) (Fig 3).

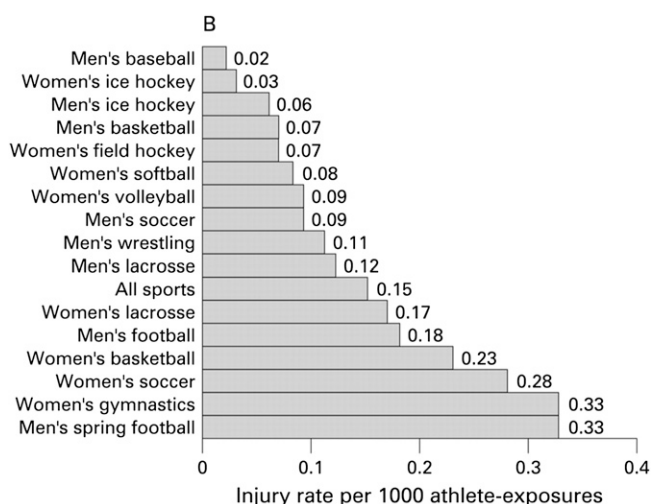
No well-designed epidemiologic studies to document ACL injury rates have been conducted in children younger than 14 years. Although there have been reports of sport-related ACL injuries in children as young as 5 years, the limited data available suggest that ACL disruptions in children younger than 12 years are rare.<sup>12–16</sup> McCarroll et al<sup>16</sup> found that of the 1722 ACL injuries diagnosed over

a 6-year period at their sports medicine center, 57 (3%) were in children 14 years and younger. The Norwegian ACL Surgical Registry collects data for all ACL surgeries performed at participating institutions nationwide. From 2004 to 2011, this registry recorded a total of only 8 to 9 ACL surgeries each year for children 11 to 13 years of age. This represents a small fraction (0.6%) of the total number of ACL surgeries recorded each year (1441) in this registry across all age groups. For the children who had surgery, the age at the time of injury ranged from 9 to 13 years.

The ACL surgery rate for 12- to 13-year-olds (3.5 per 100 000 citizens) was substantially lower than that for 16- to 39-year-olds (85 surgeries per 100 000 citizens), the age group at highest risk.<sup>9</sup> Again, these numbers underestimate the actual injury rates, because they do not account for those treated nonoperatively.

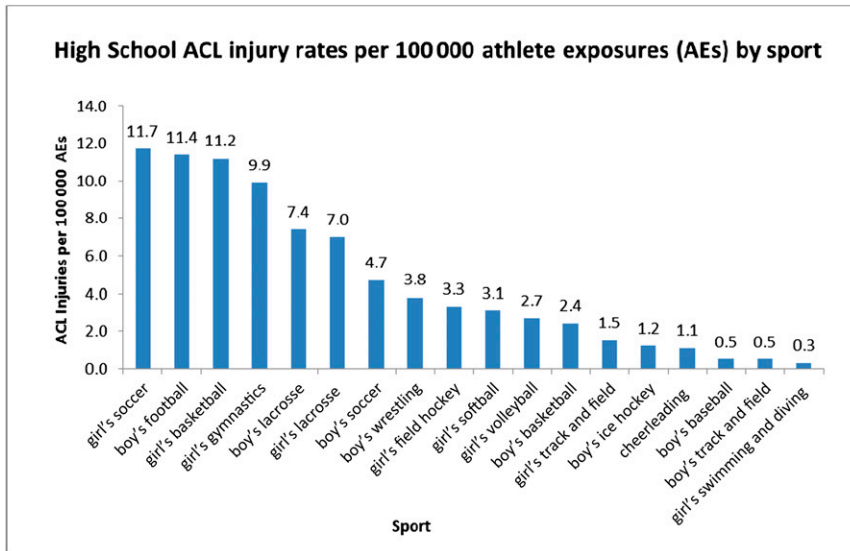
## Gender Differences

ACL injury risk begins to increase significantly at 12 to 13 years of age in girls and at 14 to 15 years of age in boys.<sup>9,12</sup> Female athletes between 15 and 20



**FIGURE 2**

Collegiate ACL injury rates per 1000 athlete-exposures by sport. (Reproduced with permission from Renstrom P, Ljungqvist A, Arendt E, et al. Non-contact ACL injuries in female athletes: an international Olympic committee current concepts statement. *Br J Sports Med*. 2008;42(6):395.<sup>10</sup>)



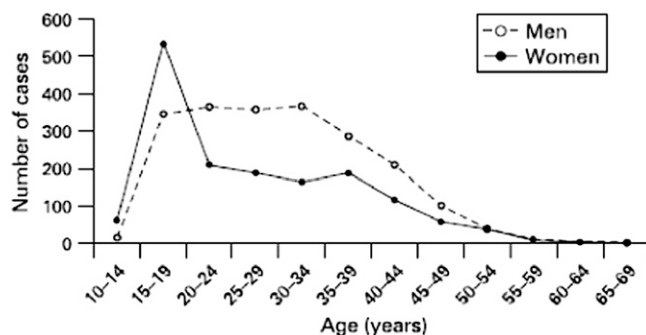
**FIGURE 3**

High School ACL injury rates per 100 000 athlete exposures (AEs) by sport. (Data from the National High School Sports-Related Injury Surveillance Study, 2007–08 to 2011–12 school years. Reproduced with permission from Comstock R, Collins C, McIlvain N. National High-School Sports-Related Injury Surveillance Study, 2009–2010 School Year Summary. Columbus, OH: The Research Institute at Nationwide Children's Hospital; 2010. Available at: <http://www.nationwidechildrens.org/cirp-rio-study-reports>.<sup>11</sup>)

years of age account for the largest numbers of ACL injuries reported (Fig 4). The gender disparity in ACL injury rates among athletes begins to appear around the time of the growth spurt (12–14 years of age for girls and 14–16 years of age for boys), peaks during adolescence, then declines in early adulthood.<sup>10,12</sup> At the high school level, ACL injury rates in gender-comparable sports (soccer, basketball, baseball/softball, track, volleyball) are

2.5 to 6.2 times higher in girls compared with boys.<sup>10,11,17</sup> In college athletics, ACL injury rates are 2.4 to 4.1 times higher for women, and at the professional level, ACL injury rates for men and women are essentially equal.<sup>4,10,18</sup>

In high school sports, ACL injuries represent a higher proportion of all injuries in female versus male athletes (4.6% vs 2.5%), with girls' basketball topping the list (6%), followed by girls' soccer, girls' gymnastics, and girls'



**FIGURE 4**

Distribution of patients in the Norwegian National Knee Ligament Registry by age and gender.<sup>a</sup> (Reproduced with permission from Renstrom P, Ljungqvist A, Arendt E, et al. Non-contact ACL injuries in female athletes: an international Olympic committee current concepts statement. *Br J Sports Med*. 2008;42(6):395.<sup>10</sup>) <sup>a</sup>Number of cases (y-axis) indicates number of ACL reconstructions.

volleyball (each 5%). Compared with boys, girls are more likely to have surgery and less likely to return to sports after an ACL injury.<sup>17,19</sup> Among female high school basketball players, knee injuries were the most common cause of permanent disability, accounting for up to 91% of season-ending injuries and 94% of injuries requiring surgery.<sup>20,21</sup>

### CONSEQUENCES OF ACL INJURY

An ACL injury at an early age is a life-changing event. In addition to surgery and many months of rehabilitation, the treatment costs can be substantial (\$17 000–\$25 000 per injury), and the time lost from school and sports participation can have considerable effects on the athlete's mental health and academic performance.<sup>22,23</sup> Although ACL injuries account for approximately 3% of all injuries in college sports, they account for 88% of injuries associated with 10 or more days of time lost from sports participation. Freedman et al<sup>24</sup> examined the academic transcripts of college students who underwent ACL reconstruction surgery. Compared with an age-matched control group, those who had surgery had a significant drop in grade point average of 0.3 points during the semester of injury ( $P = .04$ ). Similarly, Trentacosta et al<sup>25</sup> found that athletes 18 years and younger who had ACL reconstruction surgery during the school year reported that it had a negative effect on their grades.

Beyond these more immediate effects, an ACL injury also has long-term health consequences. Regardless of the type of treatment, athletes with ACL injury are up to 10 times more likely to develop early-onset degenerative knee osteoarthritis, a condition that not only limits one's ability to participate in sports but also often leads to chronic pain and disability.<sup>26,27</sup> A systematic review of a series of long-term studies suggests the rates of degenerative



knee osteoarthritis 10 to 20 years after ACL injury are more than 50%.<sup>27</sup> This means children and teenagers who suffer ACL injuries are likely to face chronic pain and functional limitations from knee osteoarthritis in their 20s and 30s. None of these studies, however, demonstrated that ACL reconstruction lowered the risk for osteoarthritis. In fact, one 5-year prospective study showed that patients who had ACL reconstruction had a higher level of knee arthrosis on radiographs and bone scans, compared with patients who did not undergo ACL reconstruction.<sup>28</sup>

## INJURY MECHANISMS

The mechanism of ACL injuries in athletes is likely multifactorial. Proposed theories to explain the mechanisms underlying ACL injury include extrinsic (physical and visual perturbations, bracing, and shoe-surface interaction) and intrinsic (anatomic, hormonal, neuromuscular, and biomechanical) variables. Identification of extrinsic and intrinsic risk factors associated with the ACL injury mechanism provides direction for targeted interventions to high-risk individuals.

At least 70% of ACL injuries are non-contact in nature<sup>29,30</sup>; however, the specific definition of a noncontact ACL injury varies from study to study. Some define a noncontact ACL injury as one that occurs in the absence of a player-to-player (body-to-body) contact. Others define noncontact ACL injury as one that occurs in the absence of a direct blow to the knee. An ACL injury resulting from body-to-body contact but with no direct blow to the knee may be classified as “noncontact ACL injury with perturbation.”

Video analysis of ACL injury during competitive sports play indicates a common body position associated with noncontact ACL injury (Fig 5) in which (1) the hip is internally rotated,

(2) the knee is close to full extension, (3) the foot is planted, and (4) the body is decelerating, leading to apparent valgus collapse of the knee or “dynamic knee valgus.”<sup>31–33</sup> ACL injury is also observed to occur when the body’s center of mass is behind and away from the base of support or the area of foot-to-ground contact.<sup>31</sup>

## RISK FACTORS

ACL injury risk in young athletes is likely multifactorial. Injury data from many fields demonstrate that numerous physical and psychological parameters affect ACL injury rates.

### Genetics

Genetic factors likely play a role, although the genetic underpinnings of increased ACL injury risk have only recently begun to be examined.<sup>34</sup>

## Hormones

Hormonal factors also likely play a role; however, results of studies investigating hormonal factors are both equivocal and controversial.<sup>35</sup> Although the female knee appears to get slightly more lax, on the order of 0.5 mm, at midmenstrual cycle, injuries tend to cluster near the start of menses at the polar opposite time in the cycle.<sup>36,37</sup>

## Previous Injury

Similar to other musculoskeletal injuries, one of the single best predictors of future ACL injury is previous ACL injury. One study found the incidence rate of ACL injury in athletes who have had ACL reconstruction was 15 times greater than that of control subjects.<sup>38</sup> Female athletes were 4 times more likely to suffer a second ACL injury in either knee and 6 times



**FIGURE 5**

Dynamic knee valgus: hips are internally rotated and adducted, tibiae are externally rotated, and feet are everted.

more likely to suffer a new ACL injury in the contralateral knee than male athletes. In fact, subsequent injuries to the contralateral ACL are twice as common as reinjury of the reconstructed ACL (11.8% vs 5.8%).<sup>39</sup> Genetic, anatomic, and neuromuscular factors likely play a role.

### Age and Gender

Although ACL injury rates increase with age in both genders, girls have higher rates immediately after the growth spurt.<sup>9–12,16</sup> It is likely that the increases in body weight, height, and bone length during pubertal development underlie the mechanism of increased risk of ACL injury with increasing age. During puberty, the tibia and femur grow at a rapid rate.<sup>40</sup> This growth of the 2 longest levers in the human body translates into greater torques on the knee.<sup>41</sup> Increasing height leads to a higher center of mass, making muscular control of this center of mass more challenging. Increasing body weight is associated with greater joint force that is more difficult to balance and dampen during high-velocity athletic movements. In pubertal boys, testosterone mediates significant increases in muscular power, strength, and coordination, which affords them with greater neuromuscular control of these larger body dimensions. Pubertal girls do not experience this same growth spurt in muscular power, strength, and coordination, which likely explains their higher rates of ACL injuries compared with pubertal boys.<sup>41</sup> That preadolescent athletes show no gender differences in ACL injury rates further supports this theory.<sup>12</sup>

### Anatomic/Anthropometric Factors

Greater weight and BMI have been associated with increased risk of ACL injury.<sup>31,42</sup> A study of military recruits found that body weight or BMI >1 SD above the mean was associated with

a 3.2 and 3.5 times greater risk of ACL injury, respectively.<sup>42</sup> In a study of female soccer players older than 8 years, BMI was a significant risk factor for knee injury.<sup>31</sup>

An increased quadriceps angle (Q angle) has been postulated as a risk factor, but there have been no prospective clinical studies to investigate the relationship between Q angle and ACL injury risk.<sup>43–45</sup> A narrow intercondylar notch, where the ACL is housed, is proposed to increase ACL injury risk, because a narrow notch tends to be associated with a smaller, weaker ACL and also could cause increased elongation of the ACL under high tension.<sup>46,47</sup> Some studies have shown that a narrow notch increases risk of ACL injury<sup>42,47,48</sup>; however, others have shown no association between notch width and ACL injury.<sup>18,49,50</sup> Subtalar joint overpronation has been associated with noncontact ACL injuries,<sup>51</sup> likely because overpronation increases anterior translation of the tibia with respect to the femur, thereby increasing the strain on the ACL.<sup>52</sup>

Generalized joint laxity and knee hyperextension were found to significantly increase the risk for ACL injury in female soccer players.<sup>53</sup> Patients with ACL injury have significantly more knee recurvatum at 10 and 90 degrees of hip flexion and an increased ability to touch palms to floor.<sup>29</sup> Athletes with generalized joint laxity had a 2.7 times greater risk of ACL injury than did those without generalized laxity, and those with increased anterior-posterior laxity of the knee, as measured by a knee arthrometer, had an approximately 3 times greater risk of ACL injury than did those without such laxity.<sup>42</sup> Joint laxity affects not only sagittal knee motion (hyperextension) but also coronal knee motion (valgus), which can strain the ACL and be related to increased risk in athletes.<sup>29,42,54</sup>

### Neuromuscular Factors

Muscle strength and coordination have a direct effect on the mechanical loading of the ACL during sport movements.<sup>55,56</sup> Poor neuromuscular control of the hip and knee and postural stability deficits have been shown to be risk factors for ACL injury.<sup>54,57</sup> Landing and pivoting sports involve a great deal of rapid deceleration and acceleration movements that push and pull the tibia anteriorly and place the ACL under stress. This tibial translation can be modulated by hamstrings and quadriceps activity.<sup>58,59</sup> In vivo studies show when subjects were asked to contract their muscles, knee laxity is reduced by 50% to 75%.<sup>58</sup> Activation of the quadriceps before the hamstrings, a pattern more frequently seen in female individuals, increases the anterior shear force that directly loads the ACL and also could be related to increased dynamic valgus alignment at initial contact during cutting and landing maneuvers.<sup>41,60–65</sup> Although fatigue is often cited as a potential risk factor for ACL injury, there are relatively few published studies to support or refute this.<sup>66</sup>

## MAKING THE DIAGNOSIS

### History

The patient with an acute ACL tear typically presents with pain, a knee effusion, a reduction in knee motion, and difficulty bearing weight. Often a “pop” is heard or felt by the athlete at the time of injury. The prevalence of an ACL tear in a pediatric athlete with a traumatic knee hemarthrosis is about 65%.<sup>67</sup> The patient with a chronic ACL tear typically presents with recurrent effusions and the sense that the knee “gives way” or is unstable with attempts at cutting, twisting, or jumping sports.

### Physical Examination

In a pediatric athlete with an acute traumatic knee effusion, the Lachman test, anterior drawer test, and pivot

shift test are clinical examinations that aid in making the diagnosis of an ACL tear.

The Lachman test is performed with the patient supine (Fig 6). The injured knee is flexed to 30 degrees. The examiner places 1 hand behind the tibia with the examiner's thumb on the tibial tubercle and the other hand on the patient's lower thigh. The tibia is pulled anteriorly. Examinations of both knees are compared. Increased anterior movement of the tibia relative to the femur without a firm end point compared with the examination of the uninjured knee suggests a torn ACL.

The anterior drawer test also is performed with the patient supine but with the knee flexed to 90 degrees (Fig 7). The examiner grasps the tibia just below the knee joint, with the examiner's thumbs placed on either side of the patellar tendon. The tibia is pulled forward. An increased amount of anterior tibial translation compared with the opposite leg or a lack of a firm end point suggests a torn ACL.<sup>69</sup> Both the Lachman and anterior drawer tests require a relaxed patient without hamstring guarding.

The pivot shift test is performed with the patient supine and the knee extended (Fig 8). The examiner stresses

the lateral side of the knee while gradually flexing the patient's knee. A "clunk" sensation occurs when the partly subluxated tibia relocates in relation to the femur, indicating that the ACL is torn. The pivot shift test is often difficult to perform in the pediatric athlete with an acute knee injury because of pain and guarding.

The Lachman test is considered the most accurate of the 3 commonly performed clinical tests for an acute ACL tear, showing a pooled sensitivity of 85% (95% confidence interval [CI] 83–87) and a pooled specificity of 94% (95% CI 92–95). The pivot shift test is very specific, namely 98% (95% CI 96–99), but has a poor sensitivity of 24% (95% CI 21–27).<sup>68,69</sup> Last, the knee arthrometer is an objective, accurate, and validated tool that measures, in millimeters, the amount of tibial translation relative to the femur while performing a Lachman test and, thus, augments the clinical examination when examining a patient with an ACL tear.<sup>70,71</sup>

### Imaging

For the pediatric athlete who presents with a traumatic knee effusion, plain radiographs should be obtained to rule out fracture, dislocation, osteochondral

injury, or physeal injury in addition to, or instead of, an ACL tear. MRI is usually not necessary to make the diagnosis of an ACL tear, as a positive Lachman test result is sufficient. However, in the pediatric patient whose physical examination is difficult to perform because of pain, swelling, and/or lack of cooperation or if there is concern for associated injuries or subtle physeal fracture, MRI may be a valuable ancillary tool.<sup>72–76</sup> MRI also can be useful for surgical planning. Sensitivity and specificity of MRI for detecting ACL tears in children has been reported to be 95% and 88%, respectively.<sup>76</sup> For meniscal tears in children, MRI has been reported to be 100% sensitive and 89% specific.<sup>72</sup> One study found that the sensitivity, specificity, positive predictive value, and accuracy of MRI for identifying all categories of pathologic changes were lower for pediatric (ages 4–14 years) versus adolescent (ages 15–17 years) patients.<sup>75</sup>

### TREATMENT

The treatment of ACL tears in the pediatric athlete is challenging and controversial. An ACL tear in a child is not a surgical emergency. Multiple timely discussions with the parents and the child about the appropriate management options and understanding their goals and expectations are very important.<sup>73</sup> Surgery is not absolute. The general indications for surgery include the patient's inability to participate in his or her chosen sport, instability that affects activities of daily living, and an associated repairable meniscal tear or a knee injury with multiple torn ligaments. Treatment of ACL injuries in the skeletally immature patient remains controversial, because standard ACL reconstructions involve the use of drill holes that cross the open physes and may potentially cause growth disturbance, such as shortening or angulation of the child's leg.<sup>8</sup> A meta-analysis of 55



**FIGURE 6**

Lachman test. (Reproduced with permission from Harris SS, Anderson SJ, eds. *Care of the Young Athlete*. 2nd ed. Elk Grove Village, IL: American Academy of Pediatrics and American Academy of Orthopedic Surgeons; 2009:413.)



**FIGURE 7**

Anterior drawer test. (Reproduced with permission from Sarwark JF, ed. *Essentials of Musculoskeletal Care*. 4th ed. Rosemont, IL: American Academy of Orthopedic Surgeons; 2010:638.)

**FIGURE 8**

Pivot shift test. (Reproduced with permission from Sarwark JF, ed. *Essentials of Musculoskeletal Care*. 4th ed. Rosemont, IL: American Academy of Orthopedic Surgeons; 2010:637.)

studies suggested that the risk of leg length difference or angular leg deviations was approximately 2% after ACL reconstruction in children and adolescents.<sup>77</sup> The authors recommended randomized controlled trials to clarify this risk more accurately. Ideally, surgical treatment of an ACL tear in a skeletally immature athlete would be postponed until skeletal maturity, and

the athlete would not develop meniscal tears during that waiting time. In the past, delay in surgical treatment was very common. Orthopedic surgeons recommended nonoperative treatment, including a brace, rehabilitation, and sports restriction for many months until skeletal maturity occurred and traditional ACL surgery could be performed safely.<sup>73,78,79</sup> For some pediatric

athletes and parents, conservative management still may be a reasonable treatment option. However, many pediatric athletes and their parents are less inclined to agree to restrict the athlete's activity. In such cases, an ACL tear in the pediatric athlete treated conservatively can lead to additional instability episodes, meniscal tears, articular cartilage damage, and early-onset arthritis.<sup>80–84</sup> Therefore, most recent literature now supports early surgery for pediatric athletes with an ACL-deficient knee and recurrent episodes of instability.<sup>82,85–87</sup> Overall, ACL surgery is about 90% successful in restoring knee stability and patient satisfaction.<sup>88</sup>

No consensus exists on the best method to treat an ACL tear in a pediatric athlete. Safe and effective surgical techniques continue to evolve.<sup>78</sup> However, the current literature suggests reasonable, evidenced-based management options that minimize the risks of iatrogenic growth plate injury.<sup>89</sup> For example, ACL surgery in a pediatric athlete is often performed via a physeal-sparing technique or a transphyseal technique.<sup>86,90–92</sup> The physeal-sparing technique avoids injury to the growth plate, but it places the graft in a nonanatomic position. An accurate understanding of the athlete's physical maturity by determining skeletal age and Tanner stage helps to identify which treatment is best for a specific patient.<sup>73,86,87,92–98</sup> The most common method of measuring the patient's skeletal age is to compare an anteroposterior radiograph of the patient's left hand and wrist to an age-specific radiograph in the Greulich and Pyle atlas.<sup>94</sup> Tanner stage can be determined by self-assessment, which has been shown to be valid and reliable.<sup>99</sup> Patients with open physes at Tanner stage III and skeletal age of less than 14 in girls and less than 16 in boys can be offered the option of activity modification, functional bracing, rehabilitation, and careful follow-up. Surgery is



indicated in skeletally immature patients with a torn ACL and an additional repairable meniscal injury and in patients who failed conservative care. In addition, ACL surgery can be elected by patients unwilling to comply with activity restrictions and bracing. Parents and patients who request surgery before maturation of the growth plates should be counseled about the risk of angular or longitudinal growth injury and the possible need for additional surgery.<sup>16,100–103</sup>

Most orthopedic surgeons select a surgical treatment option based on the patient's skeletal and physiologic age. For example, in the high-risk, most skeletally immature athlete (skeletal age less than 11 in girls and less than 13 in boys, and Tanner stage I or II) an extraphyseal procedure using a band of the iliotibial tendon or a hamstring tendon graft passed over the top of the lateral femoral condyle and through a groove in the anterior tibia is a reasonable surgical option.<sup>15,103–106</sup> Both of these extraphyseal procedures avoid the growth plate to prevent the risk of growth disturbance. A third option for the completely immature pediatric athlete is a more technically demanding all-epiphyseal procedure using hamstring tendon grafts. Some authors have used intraoperative 3-dimensional computed tomography to confirm the precise tunnel location and minimize risk of physeal injury.<sup>89</sup>

In the intermediate-risk mid-age child (skeletal age 11 to 14 in girls and 13 to 16 in boys, and Tanner stage III or IV), the previous physeal-sparing methods may be selected; however, many of these intermediate-maturity patients are safely and more appropriately treated with transphyseal reconstruction using small 7- to 8-mm centrally placed drill holes and a soft tissue graft, such as the hamstring tendons or an allograft.<sup>106–109</sup> Physeal injury can be minimized by us-

ing a small drill hole and soft tissue grafts and by placing the fixation away from the physis. Patients and parents should be counseled that there remains a small risk of physeal injury and a possibility of additional surgery for angular or growth disturbance.

Last, adolescents who are approaching skeletal maturity (skeletal age older than 14 in girls and older than 16 in boys, Tanner stage V) can undergo anatomic ACL surgery with tibial and femoral drill holes and the surgeon's graft of choice with minimal risk of physeal injury.<sup>82,110,111</sup> Autografts and allografts are both reasonable graft choices depending on the patient and surgeon preferences. Autografts have a lower graft failure rate in 2 studies.<sup>112,113</sup>

Rehabilitation after ACL surgery may need to be modified for the individual patient and the particular surgical procedure. In general, a graduated rehabilitation program emphasizing full extension; immediate weight bearing; active range of motion; and strengthening of the quadriceps, hamstrings, hip, and core can be started in the first few weeks after surgery. Progressive rehabilitation during the first 3 months after surgery includes range-of-motion exercises, patellar mobilization, proprioceptive exercises, endurance training, and closed-chain strengthening exercises. Straight-line jogging, plyometric exercises, and sport-specific exercises are added after 4 to 6 months. Return to play typically occurs 7 to 9 months after surgery.

### Return to Sport

Studies of competitive athletes, most of whom were older than 18 years, in a variety of sports have demonstrated that 78% to 91% returned to sports participation after ACL reconstruction.<sup>114</sup> However, only 44% to 62% returned to their previous level of athletic performance.<sup>114–119</sup> Female athletes were less likely than male

athletes to return to sports after ACL injury or ACL reconstruction.<sup>19,119,120</sup>

## ACL INJURY PREVENTION

### Bracing

It is unlikely that prophylactic bracing can decrease the risk of ACL injury. The relative effects of 6 different brace designs on anterior tibial translation and neuromuscular function were studied in chronically unstable ACL-deficient patients.<sup>121</sup> Bracing decreased anterior tibial translation in the range of 30% to 40% without the stabilizing contractions of the hamstrings, quadriceps, or gastrocnemius muscles. With muscle activation and bracing, anterior tibial translation was decreased between 70% and 85%. However, the braces slowed hamstring muscle reaction times. A brace with a 5-degree extension stop decreased extension on landing.<sup>122</sup>

Functional bracing after ACL reconstruction has been studied using randomized controlled cohorts placed into braced or nonbraced groups.<sup>123</sup> The braced group was instructed to wear a functional knee brace for all cutting, pivoting, or jumping activities for the first year after ACL reconstruction. There were no differences between groups in knee stability, functional testing, subjective knee scores, and range of motion or strength testing, and the investigators concluded that postoperative bracing did not change outcomes. Data are insufficient at this time to determine whether functional bracing decreases the risk of ACL injury or reinjury. Knee bracing does not improve functional performance of subjects after ACL reconstruction and may actually reduce running and turning speed.<sup>124</sup>

### Neuromuscular Training Programs

Although ACL injuries occur too quickly for reflexive muscular activation,

athletes can adopt or “preprogram” safer movement patterns that reduce injury risk during landing, pivoting, or unexpected loads or perturbations during sports movements.<sup>54,60</sup> With sufficient neuromuscular control of knee position to avoid dynamic valgus, knee stability may be improved during competitive sport and the risk of ACL injury can be significantly reduced. A collection of prospective cohort studies and randomized controlled trials have examined the effect of neuromuscular training programs on ACL, knee, and other lower-extremity injuries in soccer, basketball, volleyball, and handball (Fig 9).<sup>22,125–137</sup> Some studies used only 1 or 2 types of exercises, such as plyometric exercises and/or balance exercises, and others applied a more comprehensive approach by including plyometrics (repetitive jumping exercises designed to build lower-extremity strength and power), strengthening, stretching, and balance training.

Systematic examination of the data extracted from these studies leads to a few potentially valuable generalizations.<sup>138–140</sup> Plyometric training combined with technique training and feedback to athletes regarding proper form were the common components of programs that effectively reduced ACL injury rates. Balance training alone may not be sufficient to reduce ACL injury risk. Although some of the effective programs did not include strength training, those that did were among the most effective at decreasing ACL injury rates. ACL injury reduction was greatest for soccer athletes, and combined pre- and in-season training was more effective than pre- or in-season training alone. With respect to age, the greatest reduction in injury risk was demonstrated for female athletes in their mid-teens (14–18 years) compared with those in their late teens (18–20 years) and adults (>20 years), with 72% risk reduction for those <18 years of age

and 16% risk reduction for those  $\geq 18$  years of age. This suggests the best window of opportunity for ACL injury risk reduction may be during early pubertal maturation, at or just before girls’ neuromuscular risk factors start to become evident and ACL injury rates in girls dramatically increase. It is unknown whether neuromuscular training or other interventions can modulate the increased risk of early-onset degenerative knee arthritis after ACL injury.<sup>141</sup>

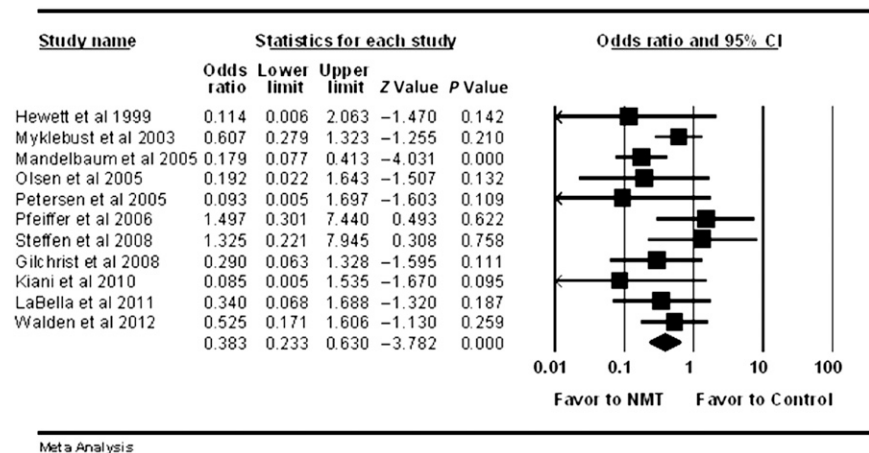
More information about specific evidence-based neuromuscular training programs can be found in the respective articles describing their study results.<sup>125–137</sup> In addition, the AAP has compiled a series of evidence-based resources that include instructional videos for pediatricians, athletes, and coaches who would like to learn more about neuromuscular training and how to perform the preventive exercises (<http://www.aap.org/cosmf>).

### CONCLUSIONS AND GUIDANCE FOR CLINICIANS

1. The number of ACL injuries in young athletes has increased over the past 2 decades, coincident with the growing number of children and adolescents participating in or-

ganized sports, intensive sports training at an earlier age, and greater rate of diagnosis because of increased awareness and greater use of advanced medical imaging.

2. Intrinsic risk factors for ACL injury include higher BMI, subtalar joint overpronation, generalized ligamentous laxity, and decreased neuromuscular control of the trunk and lower extremities.
3. ACL injury rates are low in young children and increase sharply during puberty, especially for girls, who have higher rates of ACL injuries than boys do in similar sports.
4. Although there likely are multiple factors underlying the differences in noncontact ACL injury rates in male and female athletes, neuromuscular control may be the most important and most modifiable factor.
5. ACL injuries often require surgery and/or many months of rehabilitation and substantial time lost from school and sports participation.
6. The best physical examination test for an ACL tear is the Lachman test.
7. MRI can be valuable for diagnosing ACL tears and associated meniscal and chondral injury in



**FIGURE 9**

Reduction of noncontact ACL injury with neuromuscular training. (Reproduced with permission from Myer GD, Sugimoto D, Thomas S, Hewett TE. The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. *Am J Sports Med.* 2013;41(1):209.<sup>138</sup>)

the pediatric athlete whose physical examination is difficult to perform because of pain, swelling, and lack of cooperation.

8. An ACL tear in a youth athlete is not a surgical emergency. Multiple discussions with the athlete and parents may be needed to understand the athlete's goals and parental expectations and to educate the family about possible treatment options.
9. The patient's skeletal age, measured by an anteroposterior radiograph of the left hand and wrist, and Tanner stage are helpful for the physician in deciding the most appropriate treatment of an ACL tear in a skeletally immature athlete.
10. Pediatricians and orthopedic surgeons treating young people with ACL injuries should advise them that regardless of treatment choice, they are at increased risk of early-onset osteoarthritis in the injured knee. Such discussions should be appropriately documented in the patient's medical record.
11. Musculoskeletal changes that decrease dynamic joint stability in high-risk female athletes and potentially lead to higher injury rates in this population could be modified if neuromuscular training interventions are instituted in early-middle adolescence, when the neuromuscular risk factors for ACL injury start to develop.
12. Neuromuscular training appears to reduce the risk of injury in adoles-

cent female athletes by 72%. Prevention training that incorporates plyometric and strengthening exercises, combined with feedback to athletes on proper technique, appears to be most effective.

13. Pediatricians and orthopedic surgeons should direct patients at highest risk of ACL injuries (eg, adolescent female athletes, patients with previous ACL injury, generalized ligamentous laxity, or family history of ACL injury) to appropriate resources to reduce their injury risk (<http://www.aap.org/cosmf>). Such discussions also should be appropriately documented in the patient's medical record.
14. Pediatricians and orthopedic surgeons who work with schools and sports organizations are encouraged to educate athletes, parents, coaches, and sports administrators about the benefits of neuromuscular training in reducing ACL injuries and direct them to appropriate resources (<http://www.aap.org/cosmf>).

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