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Paediatric Anterior Cruciate Ligament Tears: Epidemiology, Evaluation, and Evolving Treatment Strategies

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Abstract

Introduction: Anterior cruciate ligament (ACL) tears in paediatric patients are increasingly recognized due to rising sports participation and improved imaging. Given the presence of open physes, treatment decisions must balance the need for knee stability with the risk of growth disturbance. This review outlines current approaches to diagnosis, surgical techniques, graft selection, postoperative rehabilitation, and complications in skeletally immature patients.

Methods: This review summarizes recent literature on paediatric ACL injuries, including epidemiology, injury patterns, surgical management strategies, graft options, rehabilitation protocols, and complication rates. Emphasis is placed on the rationale behind technique selection based on skeletal maturity and long-term outcomes.

Results: Surgical reconstruction has become the preferred treatment for most paediatric ACL injuries to prevent secondary damage and restore knee stability. Several physal-sparing and transphysal techniques are available, with selection guided by skeletal age and growth remaining. All-epiphyseal and extraphyseal techniques avoid crossing the physis, while transphysal reconstruction is safe in adolescents nearing skeletal maturity. Hamstring and quadriceps tendon autografts are most commonly used, while bone-patellar tendon-bone grafts and allografts are generally avoided in younger patients. Graft failure and growth disturbance remain key concerns, with retear rates reaching up to 20% and growth abnormalities occurring in 1–5% of cases. Rehabilitation protocols are evolving toward milestone-based progression, with return to sport typically delayed at least 12 months. However, re-injury rates remain high in this population.

Conclusions: ACL injuries in paediatric patients require a nuanced, age-specific approach. Surgical reconstruction using physal-respecting or transphysal techniques offers favorable outcomes when matched to skeletal maturity. Careful graft selection, individualized rehabilitation, and delayed return to sport are essential to optimize results and reduce complications. Ongoing research is needed to refine surgical strategies, compare graft types, and establish evidence-based rehabilitation and return-to-sport guidelines.

Keywords: Paediatrics, Anterior Cruciate Ligament Tears, Epidemiology, Evaluation, Evolving Treatment Strategies

Introduction

As an increasing number of children participate in competitive-level sports year-round and begin specializing in sports at younger ages, the incidence of paediatric anterior cruciate ligament (ACL) tears has risen significantly. This increase can partially be attributed to advancements in diagnostic techniques and the emergence of subspecialists skilled in identifying injuries in young athletes [1]. Current literature highlights a growing trend towards early operative treatment to both restore

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joint stability and avoid progressive meniscal and chondral damage. However, optimal treatment strategies in this demographic are still debated as both conservative rehabilitation methods and ACL reconstructive surgery carry age-specific risks and benefits, as discussed later in this chapter.

Epidemiology

In the United States, approximately 38 million paediatric athletes participate in organized sports each year, with this number projected to rise. The Centers for Disease Control (CDC) estimates that nearly 2 million high school and more than 4 million athletes under age 14 are treated for sports injuries annually [2,3].

While the true prevalence of ACL injuries in this population is not fully understood, Shea et al found that ACL injuries accounted for 6.7% of total and 30.8% of all knee injury claims among soccer players aged 5-18 years old in the United States. A 2012 study reported that ACL injuries constitute nearly a quarter of all high school knee injuries [4]. Furthermore, in 2017, Beck et al concluded that the incidence of paediatric ACL tears had significantly increased over the past 20 years, particularly in high school athletes [5]. Similarly, a New York State epidemiological analysis reported a threefold increase in paediatric ACL reconstruction (ACLR) surgeries over the past two decades [6]. Similar trends have been observed globally, with the European Society for Sports Traumatology, Knee Surgery, and Arthroscopy noting a near two-fold increase in the last ten years.

Risk Factors

The rising incidence is believed to be linked to factors such as single-sport specialization, an increase in year-round play, and a greater focus on intense training regimens. Among the group most at risk for ACL tears—high school athletes—female soccer players experience the highest rate of injury, followed by male football players. Additionally, sports such as basketball, lacrosse, gymnastics and wrestling are also associated with a higher risk of ACL injury [7].

Regardless of sport, females have a 1.4 times higher risk of ACL injury than their male counterparts. This disparity can be attributed to post-pubertal morphological risk factors found in females, including greater anterior tibial laxity, higher Q angle, smaller ligament diameter, decreased hamstring strength, decreased roof inclination angle, altered neuromuscular control, and a smaller intercondylar notch width index and volume [7–9].

Moreover athletes who have undergone ACLR and return to sport have a 30-40 times greater risk of secondary ACL rupture, whether ipsilateral or contralateral, compared to young athletes without prior injury [10]. Studies suggest this heightened risk for reinjury may stem from abnormal knee proprioception,

which affects coordination of hip-ankle motion, as well as quadriceps strength asymmetry, leading to altered compensatory mechanics around the knee [11,12].

Injury Prevention

As the rate of ACL ruptures continues to rise—often resulting in devastating consequences for young athletes—the importance of prevention has become a focal point of research. Neuromuscular training (NMT) programs have been shown to be an effective intervention to reduce ACL injuries, especially when they incorporate multicomponent training exercises across at least three of the following domains: strength, plyometrics, agility, balance, and flexibility [13].

Injury prevention programs can be implemented according to the “ABCs.” The first component, Age (“A”), is critical. Myer et al found that fewer ACL injuries were documented in younger athletes who performed NMT compared to older athletes. Their findings suggest that the optimal time to implement these programs is during pre- or early adolescence, before puberty introduces changes in biomechanics that elevate injury risk [14].

The second component, Biomechanics (“B”), highlights the significance of joint loading. Current research suggests that factors such as increased knee abduction moments, limited knee flexion angles, greater ground reaction force, asymmetrical landing patterns, and lateral trunk flexion all contribute to elevated injury risk, which can be modified through NMT [15].

Compliance (“C”) is the third element to consider in the ABCs of ACL injury prevention. A 2012 study reported that when NMT program compliance rates were above 66%, there was an 82% reduction in ACL injury. In contrast, when compliance dropped below this threshold, the reduction fell to 44%, and at less than 33% compliance, it dropped further to just 12%. Therefore, fostering proper participation and commitment among young athletes is essential for the effectiveness of NMT programs [16].

Duration (“D”) is the final factor. Sugimoto et al reported a direct association between the duration and frequency of NMT programs and a reduction in ACL injuries. Their study suggested that longer and more frequent training sessions yielded greater prophylactic efficacy, recommending multiple sessions of over 20 minutes each week to prevent approximately 68% of ACL injuries. Additionally, the strength enhancements provided by NMT were not observed until after six weeks of participation, underscoring the need for pre-season NMT implementation [17].

Exercise variety, as mentioned above, is also a key component of successful NMT programs. Multiple studies have concluded that a combination of strength training, balance, plyometrics, and proximal muscle control produce a synergistic effect,

leading to more significant reductions in ACL injury rates than single-component training programs alone [18].

A final part of ACL injury prevention involves feedback from instructors and coaches. Studies have shown that providing instructional videos to alpine skiers resulted in a 62% decrease in ACL injuries, while active feedback during NMT has been effective in correcting knee alignment. Sugimoto et al highly recommend using verbal cues while athletes perform neuromuscular training to enhance injury prevention outcomes [19].

Diagnosis and Evaluation

Clinical Exam

The history and physical examination are critical components in the evaluation of ACL injury. Paediatric patients typically present with similar symptoms as adults, often describing an audible “pop” during a twisting motion at the knee, followed by the development of hemarthrosis over the initial 6 to 16 hours after injury [2, 20]. It is essential to clarify the mechanism of injury, the patient’s weight-bearing status, and whether the injury is acute, subacute, or chronic.

Given that paediatric patients may be guarded or uncooperative during the physical exam, it can be beneficial to start with the unaffected knee to establish baseline range of motion, joint laxity, alignment, and any limb-length discrepancy [21]. When assessing the injured knee, palpation should be used to detect effusion and evaluate the physes of the distal femur and proximal tibia, tibial tubercle apophysis, patella, and patellar retinaculum. Any tenderness at the joint lines should be noted. Range of motion of the knee should be evaluated along with a complete examination of all other ligamentous structures [2].

Historically, ACL injury has been tested with the Lachman maneuver and anterior drawer tests, but the pivot shift test may be a better indication of ligamentous function and stability. In the acute setting, however, pain may prevent the maneuver from being performed properly [20]. It is important to note that these exams are less effective in diagnosing partial ACL tears..

Radiologic findings

Initial imaging should include the routine knee radiographs. These images are essential for assessing skeletal maturity, identifying any anatomic variations, and ruling out tibial eminence fractures. MRI is the gold standard to diagnose an ACL tear and can determine whether the tear is complete or partial as well as identify any associated ligamentous or meniscal pathology [2]. Primary signs of ACL rupture include abnormal signal intensity, irregular ligament course, and ligamentous discontinuity [21]. Although often considered overused, MRI has demonstrated a sensitivity of 95% and

specificity of 88% in detecting paediatric ACL tears, making it a valuable diagnostic tool when employed correctly [22].

Assessment of skeletal maturity

In paediatric patients considering ACLR, understanding the patient’s level of maturity—prepubescent versus pubescent—can help guide surgical management. Therefore, it is important to assess skeletal and physiologic age alongside chronological age.

Physiological maturity is best classified using the Tanner staging system, with prepubescent patients categorized at Tanner stage 2 or below. Skeletal maturity can be assessed through various methods, most commonly through hand and wrist radiographs compared to the Greulich-Pyle atlas [23]. Prepubescent patients have a bone age of less than 12 years for males and less than 11 years in females, while pubescent patients have a bone age of 13 to 16 years in boys and 12 to 14 years in girls [2]. It is important to assess the skeletal maturity to guide surgical treatment and avoid potential iatrogenic physeal injury and leg-length discrepancy.

Concomitant injuries

Paediatric patients with ACL rupture frequently sustain concomitant chondral, meniscal, or ligamentous damage. A recent 20-year study found that 54% of paediatric and 71% of adolescent patients who underwent ACLR had at least one concomitant soft tissue injury. Factors such as increased age, higher BMI, and contact injuries were identified as risk factors [24]. Another study found that soccer and football players were more likely to report concomitant injuries, likely due to the higher incidence of direct contact during these sports [21].

Lateral meniscus tears are generally believed to occur simultaneously with ACL injuries, while medial meniscal tears are more commonly associated with chronic injuries in patients undergoing delayed ACLR [25]. Regardless of timing, meniscal tears linked to ACL ruptures warrant careful evaluation and intervention, as their prevalence can be as high as 69.3%. Damage to these structures is a significant risk factor for the future development of osteoarthritis [8].

Treatment

Nonoperative Management

Historically, children with ACL tears have been treated nonoperatively with bracing and activity modifications, and surgery is delayed until the patient reaches maturity. However, studies have shown that delaying surgery can lead to recurrent instability, chondral and meniscal damage, osteoarthritis, and decreased functional outcomes [26–28]. Additionally, nonoperative management involves compliance with activity restrictions and frequent monitoring [29, 30]. Therefore, surgeons have been more proactive about early stabilization

and surgical management has gained support [21]. However, there is ongoing debate about which technique is optimal, especially given the overarching concern for iatrogenic physal disturbance resulting in growth arrest.

Surgical Techniques

ACL Repair

The first surgical treatment of an ACL tear was an ACL repair performed by Mayo Robson in 1897 [31]. Since then, open repair went out of favor as ACL reconstruction showed better outcomes and became adopted as the standard of care. However, in the past two decades, there has been a renewed interest in arthroscopic ACL repair due to advancements of imaging technology and techniques [32]. Primary suture anchor ACL repair is minimally invasive and offers advantages such as eliminating the need for drilling tunnels or harvesting grafts, and the procedure can be completed quickly. Additionally, it is important to note that the implications of a failed ACL repair differ from a failed ACL reconstruction; a revision of an ACL repair is more similar to a primary reconstruction, as no tunnels are drilled and no grafts harvested [33]. Previous studies indicate that early surgical intervention and proximal tears are associated with positive outcomes. Although ACL repair may be a viable surgical option for paediatric patients, further research is needed to better understand its long-term outcomes.

Bridge-Enhanced ACL Repair (BEAR)

The Bridge-Enhanced ACL Repair (BEAR) is a new technique that has recently garnered attention. This method integrates suture ACL repair with absorbable collagen matrix and is placed between the torn ends of the ACL [34]. The scaffold is passed through the tibial tunnel and anchored to the lateral femoral cortex. Autologous blood is then added to the scaffold allowing it to conform to the intra-articular notch. Ideal candidates for this procedure are patients who have sustained injuries within 50 days prior to surgery and have an intact tibial stump for attachment. A significant advantage of this technique is that it preserves healthy tendons and avoids the need for a graft, which can lead to reduced postoperative strength loss [35].

While research is still limited, initial studies indicate that BEAR may be a viable alternative to ACL reconstruction. A randomized controlled trial comparing BEAR to hamstring autograft showed noninferior outcomes at the two-year follow-up [34]. Similar findings were reported in a subsequent 6-year follow-up study, which found no differences in outcome measures between patients who underwent BEAR compared to hamstring autograft. However, they did find that BEAR patients had hamstring strength equivalent to the contralateral leg, whereas the hamstring autograft group experienced a strength reduction of over 60% in comparison to the contralateral knee

[36]. However, it is important to note that current research does not include paediatric patients undergoing the BEAR procedure. Thus, while there is promising potential for BEAR in younger populations, further investigation is essential to assess its outcomes in this demographic.

Extraphyseal

ACL reconstruction without bone tunnels was first performed by Dr. Lyle Micheli as a modification of the MacIntosh extra-articular tenodesis procedure described in 1976. This technique uses the iliotibial (IT) band for a combined intra- and extra articular reconstruction [37, 38]. There are several advantages to this procedure such as the avoidance of transosseous tunnels, which minimizes injury to the physes and facilitates revision surgery [37]. It also provides additional stability as the extra-articular tenodesis is analogous to the anterolateral ligament [39, 40]. Indications for this procedure are prepubescent children who are Tanner stages 1-2 or skeletal age < 11 years old in females and < 12 years old in males.

The epiphyseal technique without bone tunnels has been shown to be safe and effective. A retrospective review by Willimon et al. found excellent functional outcomes (IKDC = 97 and Lysholm = 95), a graft failure rate of 14% and reoperation rate of 27%.41 Kocher et al reported similarly high functional outcome scores in 44 patients (IKDC= 96.7 ± 6.0 and Lysholm = 95.7 ± 6.7) but found a lower retear rate of 4.5%.37 In their later study, they reported that among 237 patients who underwent ACL reconstruction using IT band, 96.8% of the knees were grade A on the Lachman test, 98.8% were grade A on the pivot-shift test, and 48% had lateral thigh asymmetry—although only 1.6% experienced pain [42].

All epiphyseal

Anderson et al. first introduced the all epiphyseal technique and multiple iterations have been described since [43–45]. This technique involves drilling femoral and tibial tunnels only within the epiphysis and restores the ACL anatomic footprint. Fluoroscopy is used to ensure that the physis is not violated intraoperatively. Drilling can be performed either antegrade or retrograde into the joint, and multiple fixation options are available. Over the past few years, multiple retrospective studies have reported on the all-epiphyseal technique. Cruz et al. found that among 103 patients who underwent all-epiphyseal ACL reconstruction, the complication rate was 16.5% and graft failure rate of 10.7% [46]. Nawabi et al. evaluated postoperative physal-specific magnetic resonance imaging (MRI) in 15 patients and found that 67% of the patients had tibial physal injury involving 2.5% of the surface area but only 1 patient had femoral physis disruption with minimal surface area involvement (1.5%) [47]. They also reported that there were no cases of growth arrest, angular deformity, or leg length

discrepancy.

Transphyseal

In the transphyseal approach, tunnels are created that pass through the open growth plates of both the femur and tibia, allowing a soft tissue graft to be positioned across them. The partial transphyseal approach drills across either the femoral or tibial physes while preserving the other side [21]. This technique is ideally suited for nearly skeletally mature adolescents, particularly boys with bone age 15 years and older and girls of 13 years and older, as they face a lower risk of growth disturbances.

While numerous studies have demonstrated the safety and efficacy of this technique, some animal studies have raised concerns about potential growth arrest, limb shortening, and deformity, especially when large tunnels are created or placed eccentrically through the physis [48–51]. However, most studies indicate low rates of growth disturbances when using transtibial drilling techniques with vertically oriented femoral tunnels. Recent research suggests that oblique, anatomic femoral tunnels can provide improved stability and better restore knee biomechanics [52]. A systematic review by Petersen et al. found no significant difference in graft failure rates between transtibial (10.8%) and independent drilling (11.4%) [53]. In a study by Kocher et al., which evaluated outcomes of the transphyseal technique in patients with an average skeletal age of 14.4 years, no angular deformities or limb length discrepancies were reported [54]. Similarly, a long-term study by Calvo et al., with a mean follow-up of 10 years, assessed the outcomes of 27 skeletally immature patients who underwent ACL reconstruction using the transphyseal technique with vertically oriented tunnels and hamstring autograft. They reported a graft failure rate of 14.8% as well as an IKDC score of 94 and a mean Lysholm score of 92 [49].

Graft Choice

There are a variety of graft types used for paediatric ACL reconstruction, including hamstring autograft and quadriceps autograft. Bone-tendon grafts are typically not recommended for younger patients due to the risk of harvesting close to the physis, which can ultimately lead to growth disturbances. Historically, hamstring autografts have been the most commonly used, particularly in all-epiphyseal and transphyseal techniques [41, 52, 55]. The iliotibial band is also a viable option for younger patients (Tanner stage 1 and 2), as the technique avoids bone tunnel drilling. Recently, there has been growing interest in the use of quadriceps autograft. A study by Todd et al. found that by 16 years old, the quadriceps tendon length and thickness increases to 8 cm and 4 mm, respectively, making this graft suitable for paediatric patients [56]. Additionally, Kohl et al. reported no graft failures and a Lysholm

score of 94 in 15 patients who underwent ACL reconstruction with a quadriceps tendon graft, although one growth disturbance was identified [50]. Similarly, Cordasco et al. reported that the use of quadriceps autograft led to excellent postoperative outcomes, including a graft failure rate of 4% and 100% return to sports rate [57].

Overall, there is a lack of comparative studies on autograft types in the paediatric population. However, allografts are generally not recommended in skeletally immature patients due to the higher failure rates. Engelman et al. conducted a case control study involving 73 patients and found that 29% of allografts failed, compared to only 11% of autografts [58]. In a study utilizing MOON data, Kaeding et al. demonstrated that paediatric patients who underwent ACL reconstruction with allograft were four times more likely to experience graft failure compared to those receiving autografts. Furthermore, they reported that the risk of graft failure with allografts more than doubles for every 10-year decrease in age [59].

Postoperative Rehabilitation and Return to Sports

Rehabilitation tailored for skeletally immature patients is critical for restoring functional knee stability and minimizing postoperative complications. Unfortunately, studies indicate that re-injury rates are alarmingly high, with 50-100% of paediatric patients who undergo ACL reconstruction likely to develop early osteoarthritis within 5-10 years [60]. Therefore, postoperative management must prioritize joint preservation, especially in cases involving concomitant meniscal pathology. Return to sport (RTS) protocols should emphasize biomechanical techniques tailored to the specific demands of each patient's sport. Moreover, it is essential to differentiate these protocols from those used for adults, incorporating modifications in the intensity of progression through each phase and establishing specific criteria for safely returning to cutting and pivoting sports.

There remains a lack of literature on the optimal rehabilitation protocol for skeletally immature patients. Greenberg et al. recommended a prolonged RTS program, noting strength and functional deficits in young patients one year after surgery [61]. This finding aligns with previous studies indicating that nearly 60% of patients do not return their pre-injury activity levels within 12 months [62]. The International Olympic Committee advises against returning to sport until at least one year after surgery, while others recommend taking two years to recover, recognizing that it takes longer to return to their pre-injury state [63]. However, delaying RTS may have implications for regaining pre-injury performance, as children develop rapidly and extended time away from their sport could hinder their progress. Protocols have shifted from time-based to milestone-based, with timelines ranging from 6 months to over a year [64]. It is also recommended that a combination of

qualitative and quantitative assessments be used to evaluate readiness for return to sport. Overall, the primary goals are to enable the patient to return to their activities safely and prevent re-injury.

Complications

Major complications of ACL reconstruction in paediatric patients include stiffness, graft failure, and growth disturbance. Stiffness is particularly common, affecting approximately 3.9% to 8.3% of young patients [65–67]. This condition typically results in limited knee motion due to factors such as improper graft placement, cyclops lesions, or arthrofibrosis [68]. Younger patients experience a higher graft failure rate compared to adults, with studies indicating that the risk of re-tear decreases by 9% for each year of age [69]. Graft failure rates have been reported to reach as high as 20%, with the likelihood of requiring subsequent knee surgery at 34.7% [70, 71]. Wiggins et al. suggests that young athletes returning to sport face a reinjury risk 30 to 40 times greater than uninjured adolescents.10 Additionally, Yabroudi et al. found a significantly higher failure rate of 14% in patients under 18 years old compared to a 2% rate in patients over 24 years old [72]. These high failure rates can be attributed to the increased activity levels and early return to pivoting sports seen in younger athletes. The most common type of growth disturbance is overgrowth suggested to be due to periosteal stimulation near the growth plate. It is essential to monitor leg length and alignment until the patient is skeletally mature. If overgrowth

occurs, minimally invasive percutaneous epiphysodesis can be performed. Although the incidence of growth disturbance remains relatively low, ranging between 1 and 5%, the potential implications warrant careful attention to accurate tunnel placement and diameter in relation to the open physis [73, 74].

Conclusion

The incidence of ACL tears in the paediatric population continues to rise, underscoring the need for early stabilization through ACL reconstruction, which has increasingly become the preferred treatment option among surgeons. In this context, it is crucial to consider skeletal age as a guiding factor in treatment decisions, as it directly influences both surgical approach and outcomes. While several surgical techniques exist—each with its own distinct advantages and disadvantages—the overall clinical outcomes for paediatric ACL reconstruction have been encouraging. It is essential to implement a tailored rehabilitation program that takes into account skeletal age and specific return to sport goals, particularly for pivoting sports that pose a greater risk for reinjury. One of the major concerns associated with ACL reconstruction in the pediatric population is graft rupture, which necessitates vigilant monitoring and follow up care.

Moreover, further research focused on ACL reconstruction in the paediatric population is imperative to refine techniques, enhance safety, and improve long-term outcomes, ensuring we effectively address both immediate injury management and the future activity levels of young athletes.

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