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REVIEW

Management of Anterior Cruciate Ligament Tears in Skeletally Immature Patients

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Abstract

Purpose of Review Anterior cruciate ligament (ALC) tears are increasingly common in skeletally immature patients, as more children and adolescents participate in intensive sports training and specialization at increasingly younger ages. These injuries were historically treated nonoperatively, given concerns for physeal damage and subsequent growth disturbances after traditional ACL reconstruction techniques. However, there is now sufficient data to suggest superior outcomes with operative treatment, specifically with physeal-sparing and physeal-respecting techniques. This article reviews considerations of skeletal maturity in patients with ACL tears, then discusses surgical techniques, with a focus on their unique indications and outcomes. Additional surgical adjuncts and components of postoperative rehabilitation, which may reduce retear rates, are also considered.

Recent Findings Current research shows favorable patient-reported outcomes and high return-to-sport rates after ACL reconstruction in skeletally immature patients. Graft rupture (ACL retear) rates are low, but notably higher than in most adult populations. Historically, there has been insufficient research to comprehensively compare reconstruction techniques used in this patient population. However, thoughtful systematic reviews and multicenter prospective studies are emerging to address this deficit. Also, more recent data suggests the addition of lateral extra-articular procedures and stringent return-to-sports testing may lower retear rates.

Summary Physeal-sparing and physeal-respecting ACL reconstructions result in stabilization of the knee, while respecting the growth remaining in children or skeletally immature adolescents. Future research will be essential to compare these techniques, given that more than one may be appropriate for patients of a specific age and skeletal maturity.

Keywords Anterior cruciate ligament · Pediatric · Adolescent · Skeletally immature · Growth disturbance

Introduction

An anterior cruciate ligament (ACL) tear is a serious injury at any age but may be especially impactful during childhood and adolescence. Beyond the trauma of the injury, there are substantial monetary costs, impacts on academic performance, time away from sports participation, and potential implications to psychosocial health at a time of critical physical, psychological, and social development. Unfortunately, ACL injuries are relatively common in young athletes, occurring at a rate of up to 51 per 100,000 children [1–3]. Female adolescent athletes are perhaps at the highest risk, with nearly 1 ACL injury per 10,000 athletic exposures, equating to a 10% risk of injury over a high school multisport career [4]. Rates of ACL tears are increasing in all age groups, but more quickly in pediatric and adolescent as compared to adult cohorts, by around 2 to 3% per year [1, 3, 5]. Rates of ACL reconstructions are also increasing more quickly than the rate of orthopedic surgeries in general, by 2.8-fold between 2004 and 2014 [6]. Multiple factors may be contributing to this increase. It has paralleled an overall increase in youth sports participation, particularly in girls. Children are increasingly participating in more intensive training and sports specialization at younger ages. There is also perhaps more awareness of ACL injuries in both the lay public and the medical community, as well as increased access to medical imaging for diagnosis. This review aims to

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discuss various treatment options for treating pediatric and adolescent ACL tears as well as their unique indications and outcomes, with a focus on the skeletally immature athlete.

Non-operative Versus Operative Management

Historically, pediatric ACL tears were treated non-operatively or with delayed reconstruction after a patient reached skeletal maturity, for fear of physeal damage from traditional ACL tunnels and resultant growth disturbances. Non-operative management consists of intensive rehabilitation to balance and strengthen the musculature around the knee, thus decreasing reliance on ligamentous restraints. Some propose activity modification, specifically avoidance of cutting and pivoting activities. Most strongly encourage the use of a brace to restrict anterior tibial translation. Successful non-operative treatment is often considered to be (1) no recurrent instability with (2) no subsequent meniscal or chondral injury.

Much of the current literature supports early operative treatment over non-operative treatment for ACL tears in skeletally immature patients. Regarding knee stability, a meta-analysis by Ramski et al. reported 75% of patients treated non-operatively to have pathologic laxity, as compared to 14% of those treated with ACL reconstruction [7, 8••]. Regarding subsequent injuries, Kolin et al. found each week of delay in surgical stabilization resulted in a 2% higher risk of medial meniscal tears—such that a 3-month delay equates to a nearly 25% increase in meniscal pathology [9•]. The rates of irreparable meniscal tears also increases with delays in surgical management, as do the rates of chondral damage in all compartments [8••, 10]. Patient reported outcomes are similar, if not better, in operatively treated patients, and return to sport rates are notably higher [7, 8••, 11]. In a systematic review by James et al., 6 to 50% of pediatric or adolescent patients with ACL tears treated non-operatively returned to their pre-injury sport, as compared to 57 to 100% of those treated with ACL reconstructions [8••].

While these findings are striking, they should be interpreted with some caution. Early studies on non-operative management may have adhered to this plan for fear of growth arrest associated with operative treatment, regardless of recurrent instability. Indeed, many patients in these studies had recurrent instability so it is understandable that they may develop additional meniscal and chondral pathology over time [12]. In contrast, Ekås et al. have reported on a cohort of 44 patients who sustained ACL tears before the age of 13 initially non-operatively, with close and consistent follow-up for a mean of 8 years [13]. Patients were transitioned to operative management in the setting of continued or recurrent instability. At last follow-up, 55% had undergone ACL reconstruction, 22/24 for recurrent subjective instability and only 2/24 each for secondary meniscal injuries or unacceptable activity levels. However, 45% did well with non-operative management, with comparable or better functional outcomes and PROs, including muscle strength, hop testing, IKDC scores and KOOS scores, as compared to those treated with delayed ACL reconstruction. While the majority of patients participated in non-pivoting sports, 23% of those treated non-operatively and 33% of those ultimately treated with an ACL reconstruction participated in pivoting sports.

Early operative management continues to grow in popularity, particularly in the USA, though non-operative management remains a common option in some regions internationally [6, 14]. While there may be an important role for non-operative treatment, challenges remain in identifying optimal candidates, ensuring robust rehabilitation and in close monitoring for continued or recurrent instability necessitating conversion to operative treatments.

Skeletal Age, Growth Remaining, and Growth Disturbances

Although treatment has shifted decidedly towards operative management of ACL tears in skeletally immature patients, growth disturbances are still of significant concern. The ACL origin and insertion are in close proximity to the distal femoral and proximal tibial physes, respectively [15]. This is especially true in younger and smaller patients, which makes avoiding the physes technically challenging. Drilling across the physis can result in bony bars and partial or full physeal arrest. Conversely, even drilling in the proximity of the physis may stimulate vascularization and overgrowth. Either can contribute to limb length discrepancies (LLDs) or angular malalignment, most commonly genus valgus [16]. For these reasons, it is very important to understand the skeletal maturity of a patient and the potential growth remaining of the injured knee.

The knee contributes to approximately 65% of overall leg length, with about 70% of femoral growth coming from the its distal physis and about 60% of tibial growth coming from its proximal physis [17, 18]. Growth remaining can be estimated in a number of ways. Maturity can be approximated based on overall growth velocities, menarchal history in girls, or through Tanner staging. Tanner staging, which includes assessments of pubic hair as well as breast development in girls and genital development in boys, may be gleaned from pediatricians' visits, and is less appropriate in the orthopedic clinic setting. Alternatively, the Tanner stage can be self-assessed by adolescents or assessed by the surgeon in the operating room. However, the latter precludes incorporating this data into pre-operative planning, making Tanner staging overall less useful [19].

Maturity, specifically skeletal maturity, is therefore perhaps best assessed with radiographic imaging, as chronologic age is known to differ significantly from skeletal age in many children. Radiographs of the left hand and wrist are most commonly used in conjunction with methods by either Sanders et al. [20] or Greulich and Pyle [21]. The Shorthand Bone Age method simplifies the Greulich and Pyle method down from a radiographic atlas to one criterion for each age category, which may be more efficiently used by clinicians [22]. More recently, a method based on an MRI of the knee was developed, with subsequent development of shorthand methods based on the same [23–25]. These methods obviate the need for imaging, other than that routinely obtained to diagnosis and treat an ACL tear.

Understanding the skeletal age of the patient gives insight into the likely amount of growth remaining at the injured knee. Skeletal maturity typically occurs around age 14 for girls and 16 for boys. The physes are assumed to be contributing to growth up to this point, at around 9–10 mm/year at the distal femoral physis and around 6 mm/year at the proximal tibial physis [17, 26]. Some amount of limb length discrepancy may be normal in the general population and is not noticeable by most people unless it exceeds 1–2 cm. To that end, ACL tears in adolescents with closing physes (i.e., < 1 cm of growth remaining) are often treated with techniques used in adults. This typically applies to girls with skeletal ages of ≥ 14 years old and boys ≥ 16 years old. ACL tears in adolescents with 1–2 years of growth remaining (i.e., 1–5 cm, typically girls 12–13 years old and boys 14–15 years old) are treated with physeal-respecting techniques. Lastly, tears in prepubescent patients (i.e., > 5 cm of growth remaining, girls ≤ 11 and boys ≤ 13) are treated with physeal sparing techniques (Table 1). Specifics of various physeal-sparing and physeal-respecting techniques are depicted in Fig. 1 and will be disused in detail below.

A significant proportion of ACL tears in skeletally immature patients occur in adolescents with closing physis, who have minimal risk for clinically significant growth disturbances [27–29]. When physeal-sparing or physeal-respecting techniques are used in the remaining patients with open physes, growth disturbances are relatively rare after ACL reconstruction, provided there is understanding and application of the principles and technical steps discussed below. A systematic review and meta-analysis by Fury et al. including 3798 skeletally immature patients reported only 2.1% of patients with a LLD > 10 mm and 0.5% with an LLD of > 20 mm [30••]. Angular deformities were similarly rare, occurring in 1.3% of patients including cases of femoral valgus (41%), tibial recurvatum (33%), and tibial varus (22%).

It is important to note that regardless of technique, all skeletally immature patients should be monitored post-operatively for growth disturbances until skeletal maturity. This necessitates hip-to-ankle radiographs preoperatively, with additional radiographs every 6 to 12 months postoperatively, which may be increasingly spaced out for those with multiple years of growth remaining. Though rare, it is important to identify the first suggestion of a possible disturbance and monitor closely thereafter to predict if they will become clinically relevant. In such cases, growth disturbances can be addressed with guided growth techniques, such as hemiepiphysiodesis for angular deformities, or epiphysiodesis for leg length discrepancy, which are hugely preferable to osteotomies or more invasive techniques that may be required to correct malalignment or limb asymmetries in skeletally mature patients.

Table 1 Anterior cruciate reconstruction techniques by patient maturity. LET = lateral extra-articular tenodesis

Maturity	Tanner stage	Skeletal age (in years)		Acceptable techniques	Graft options
		Girls	Boys		
Prepubsecent	1–2	≤ 11	≤ 13	"Physeal-sparing": Modified McIntosh (intra-/extra-articular) All-epiphyseal	Iliotibial band Hamstring vs. quadriceps
Adolescent with 1–2 years of growth remaining	2–3	12–13	14–15	"Physeal respecting": Partial transphyseal (hybrid, + / − LET) Transphyseal (+ / − LET)	Hamstrings vs. quadriceps
Adolescent with closing physes	4–5	≥ 14	≥ 16	Standard, adult-type tunnels/technique (+ / − LET)	Hamstrings vs. quadriceps vs. patellar tendon (bone-tendon-bone)

Operative Techniques

Physeal-Sparing Intra-articular and Extra-articular Over the Top Reconstruction with Iliotibial Band

The first iliotibial band (ITB) technique used for ACL deficiency was described in adults by MacIntosh et al. in 1976 and was extra-articular in nature [31]. The authors described taking a strip of distally based ITB which was passed deep to the lateral collateral ligament (LCL), then passed back superficially and sutured to itself. Micheli et al. later modified the technique, such that a slightly longer strip of ITB was not passed back, but rather was wrapped around the lateral femoral condyle in the over the top position and through the intercondylar notch to ultimately include extra-articular and intra-articular components of the reconstruction (Fig. 1A) [32]. In this technique, fixation is achieved by suturing the ITB band to the periosteum of the posterolateral aspect of the lateral femoral condyle, achieving an extra-articular restraint akin to a lateral extra-articular tenodesis. The graft is passed under the intermeniscal ligament then secondarily sutured to the anterior aspect of the tibial metaphysis distal to the proximal tibial physis. The proximal tibial epiphysis at the intra-articular tibial ACL footprint and the anterior tibial cortex just proximal to the pes anserinus undergo rasping and decortication to allow for tendon to bone healing. However, given that no transphyseal tunnels are drilled, there is theoretically no damage to the physes and no concern for tunnel widening or convergence in revision cases.

While some have described the modified Macintosh ITB technique as "non-anatomic," it appears to approximate or restore the biomechanical and kinematic properties of the knee to a greater degree than other techniques, controlling both anterior translation and rotation [33, 34]. Sugimoto et al. used 3-D motion analysis to evaluate patients' lower extremity kinematic performance in four categories of follow-up, ranging from 1–2 years, to 2–5 years, 5–10 years, and 10–20 years post-operatively [35]. They demonstrated no differences between the operative and non-operative legs during drop vertical jump and vertical simple-limb hop tests, and similarly symmetric performance between the cohorts, based on follow-up.

Clinical outcomes after ITB ACL reconstruction are similarly quite favorable. Kocher et al. reported on a cohort of 44 patients in 2005, then on an expanded cohort of 237 patients in 2018 [36, 37]. In the later study, 97% of patients had a grade A Lachman and 99% had a grade A pivot at last follow-up. Lateral thigh asymmetry at the IT band harvest site was noted in 48% of patients, but $<2\%$ reported associated pain. Patient reported outcomes (PROs), obtained at a mean of more than 6 years post-operatively, demonstrated functional scores superior to age-based normative values, with a mean Pedi-IKDC of 93.3 ± 11.0 and a mean Lysholm score of 93.4 ± 9.9, as well as high activity levels with a mean Tegner of 7.8. There were no cases of growth disturbances, and graft rupture occurred in 9 patients (6.6% of the PRO cohort, 3.6% of the overall) at a mean of 33.5 months post-operatively. Willimon et al. reported on a much smaller cohort of patients ($n = 22$) after ITB ACL reconstruction. They reported similar or better PROs as compared to Kocher et al., but a 9% revision ACL reconstruction and an overall 27% reoperation rate [38]. A meta-analysis of by Knapik et al., largely dominated by the cohort reported by Kocher et al., demonstrated an overall retear rate of 4% [39].

All-Epiphyseal Techniques

Similar to the ITB technique, all-epiphyseal (AE) techniques attempt to avoid growth disturbance altogether by sparing injury to the physes. As the name implies, tunnels are drilled so that they are completely contained within the distal femoral and proximal tibial epiphyses (Fig. 1B). Proponents have suggested that these tunnels produce more "anatomic" graft placement. However, given that the center of the femoral footprint of the ACL is approximately 3 mm away from the distal femoral physis and the vertical height of the proximal tibial epiphysis is around 16 mm in skeletally immature adolescents, there are considerable technical challenges with achieving this goal [15, 40]. Fluoroscopy and, in some instances, intra-operative computed tomography, are used to

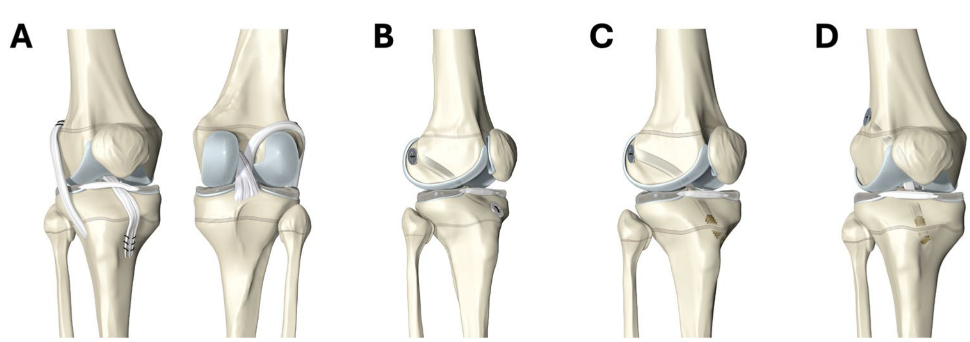

Fig. 1 Physeal sparing techniques include (**A**) over the top reconstructions with iliotibial band and (**B**) all-epiphyseal reconstructions. Physeal respecting techniques include (**C**) partial transphyseal (hybrid) reconstructions and some (**D**) transphyseal reconstructions

confirm safe and appropriate tunnel placement. Numerous all-epiphyseal techniques have been described including by Anderson [41], Ganley-Lawrence [42], and Cordasco-Green [43], each with unique tunnel drilling and fixation methods, though most utilize hamstring autograft.

Biomechanically, these AE techniques reduce anterior translation from that in an ACL deficient knee, but translation is still greater than in an ACL intact knee [33, 34, 44]. However, the impact of AE ACL reconstructions on internal rotation is still unclear, as a study by Kennedy et al. reported internal rotation to be poorly controlled, while a study by McCarthy et al. reported it to be over-constrained by AE ACL reconstruction [34, 44].

A follow-up MRI study by Nawabi et al. confirms that significant risk to the physes is low. In expert hands, an average of 1.5% and 2.1% of the femoral and tibial physes, respectively, were violated by AE ACL reconstruction. However, other reports of significant LLD (≥ 10 mm) have ranged from 0 to 27%, with a meta-analysis by Knapik et al. reporting an average rate of 4% [39, 45•, 46, 47]. Lawrence et al. have reported on a case of premature lateral physeal closure, presumably due to thermal injury from tunnel drilling [48]. Overgrowth, though, may be more common than growth arrest or angular deformities after AE ACL reconstruction, likely due to increased vascularity or a hyperemia effect following drilling in close proximity to the physis [30••].

PROs after AE ACL reconstruction are also favorable, with IKDC scores ranging from 89.7 ± 12.7 to 94.6 ± 4.9 [45•, 47, 49]. Return to sport rates are also relatively high at 97% in a study by Fourman et al., though only 71% returned at their baseline level of competition [45•]. Retear rates after AE ACL reconstruction range from 4 to 15%, at an average of 8% in a meta-analysis by Knapik et al. [39, 45•, 46, 47, 49, 50].

Partial Transphyseal (Hybrid) Techniques

Just as skeletal age is a continuum, so are ACL reconstruction techniques. Partial transphyseal (PTP) techniques, sometimes referred to as "hybrid ACLR" techniques, combine components of physeal-sparing techniques, either in the form of an over-the-top method or all-epiphyseal method on the femoral side, with a transphyseal tunnel on the tibial side, in an attempt to balance concern for physeal disruptions with the benefits of more anatomic reconstructions. Numerous combinations of PTP techniques have been reported, most commonly drilling a central, relatively vertically oriented tibial tunnel, while drilling an all-epiphyseal femoral tunnel (Fig. 1C) [51–54]. The rationale of the technique revolves around the established earlier closure of the tibial physis, as well as the more significant contribution of the femoral physis to overall limb length as discussed previously. The peripheral location of the femoral tunnel also carries a higher risk of physeal arrest [55].

A number of modifications have been further made to PTP techniques to minimize damage to the physis. Larger tunnels inherently damage a larger proportion of the physis, though the percentage decreases with increasing patient age and size [56–58]. Physeal injuries of as little as 7–9% of the surface area of the physis can result in growth disturbances in animal models [59]. Luckily, multiple studies using 3-D reconstructions of pediatric and adolescent patients have estimated the volume removed to be < 7% in the tibia and < 9% in the femur when reamers up to 9 mm in diameter are used, with on average a 1.1% increase per 1 mm increase in reamer diameter [56–58, 60]. Some also advocate for more vertical tunnels, as they cross the physis more perpendicularly creating a smaller zone of injury. Indeed, Kercher et al. demonstrated that increasing the tibial tunnel drill angle from 45° to 70° relative to the horizontal decreases the volume of physis removed from 4.1 to 3.1% [58].

Left unfilled, reamed transphyseal tunnels risk healing as a bony bar. A bone plug, for example from a patellar tendon bone-tendon-bone (BTB) autograft, will also create a bony bar and potential growth disturbances if placed across the physis, as will most implants, such as interference screws. Soft tissue grafts, however, if placed into a reamed tunnel with a relatively snug fit, should prevent bony bar formation within the tunnel. Using a canine model, Stadelmaier et al. demonstrated no disruption of the physes up to 4 months after surgery using fascia lata autograft for a transphyseal ACL reconstruction [61]. Moreover, bony bar resection techniques typically call for reaming out the bony bar and placement of an interposition graft, such as muscle, tendon, or fat. For these reasons, soft tissue grafts, specifically hamstring and quadriceps autograft, are preferred for PTP techniques.

Few studies adequately report outcomes after PTP ACL reconstruction to comprehensively analyze the success of the technique, which is further confounded by the significant variation across techniques. Chambers et al. and Willson et al. both reported on small ($n < 25$) case series of patients after PTP ACL reconstructions using AE femoral tunnels and transphyseal tibial tunnels [62, 63]. PROs were favorable, with a mean Pedi-IKDC of 96.0 ± 3.5 in the study by Willson et al. The groups reported LLDs > 1 cm in 13% and 9% of patients in the respective studies as well as genu valgus is 13% of patients in the study by Chambers et al. Graft failures occurred in 8% of patients in the study by Chambers et al. and were not reported by Willson et al. [62, 63].

Physeal-Respecting Transphyseal Techniques

The majority of ACL tears in skeletally immature athletes actually occur in adolescents with 1–2 years of growth remaining, and thus relatively lower risk for clinically significant growth disturbance than in prepubescent counterparts

[27–29]. However, care must be taken to appropriately select patients with limited growth remaining and transphyseal techniques (Fig. 1D) must still be mindful of the ongoing function of the physis. Smaller reamers and soft tissue grafts may be preferred, for reasons previously described.

While some studies report no growth disturbances after transphyseal ACL reconstruction in this population[27–29], limb length discrepancies and angular deformities can occur. These include growth arrest and relative shortening of the operative limb, genu valgus, and recurvatum. However, most reports of such complications include small numbers of patients (5–6% of patient cohorts), with some reported to be asymptomatic and few requiring operative treatment [64–68]. These findings are despite some cohorts reporting significant (> 5 cm) increases in patient height after transphyseal ACL reconstructions [28, 29].

Clinical outcomes after transphyseal ACL reconstructions are relatively favorable. A systematic review by Buckle et al. reported a mean Lysholm score of 94.3 and IDKC of 93.6, with high levels of activity post-operatively (average Tegner 6.8) [69]. Retear rates vary across studies ranging from 3 to 17%, with an average of 5% in the aforementioned systematic review [27, 29, 50, 69, 70].

ACL Repair

ACL repair is a theoretically attractive alternative to ACL reconstruction in skeletally immature patients. It poses limited risk to the physes with no donor site morbidity and potentially expedited recovery. Vascularity and cellularity in and around the ACL are higher in children than in adults [71, 72]. Much of the vascularity is preserved in proximal ACL tears amenable to repair, as it originates truncally from the septum. Biologically, it seems logical that ACL repair would be more successful in younger patients. However, children and adolescents often have higher activity levels and place more athletic demands on a repaired ACL than their adult counterparts.

Indeed, results after ACL repair in young active patients have been mixed. Bigoni et al. and Dabis et al. reported on small ($n = 5$ and $n = 20$, respectively) cohort studies with average ages of 9.2 (range 8–10) and 12.9 (range 5–16) years old, respectively, with Lysholm scores > 90, high rates of return to high levels of activity and no growth disturbances [73, 74]. Turati et al. reported similarly good patient reported outcomes and return to sports on a cohort of 14 patients age 9.2 ± 2.9 years at the time of ACL repair [75]. The authors similarly reported no growth disturbances, but did report a 21% retear rate after ACL repair with a mean of 5.7 years of follow up. By contrast, Gagliardi et al. reported a retear rate of 49% after ACL repair, as compared to 5% in a transphyseal ACL reconstruction control group [76]. In larger studies of ACL repair across age ranges, younger cohorts consistently retear at higher rates than older cohorts [77•, 78••, 79]. This sparse data suggests that young active patients may have favorable aspects of their recovery following ACL repair, such as decreased pain, increased strength, and high rates of return to sports, but that retear rates may be higher than those with ACL reconstruction techniques. More follow up data specific to skeletally immature patient is warranted to better understand the future role of ACL repair in pediatric and adolescent athletes.

Comparisons of Operative Techniques

As discussed, operative techniques for ACL reconstruction in children are typically dictated by skeletal age. However, skeletal age is a continuum, and some patients may be appropriate for multiple techniques. For example, an adolescent with 2 years of growth remaining may reasonably be considered for either a physeal-sparing or physeal-respecting transphyseal technique. Additionally, both ITB and AE techniques may be appropriate techniques for a patient with 3–4 years of growth remaining. Interestingly, most surgeons who favor the AE technique as a physeal-sparing option acknowledge that the very young patient with an ACL tear—for example, those under 10–11 years old—may have bony epiphyses, at least on the tibial side, that are too small to safely place AE tunnels without undue risk of physeal injury. Thus, these authors have suggested that the ITB ACLR technique be utilized in these smaller knees, even though they may prefer AE for a slightly older age. As the major ITB ACLR studies have been described for ages ranging between 3 and 14 years old, it has been shown to be reliable and safe in prepubescent children of any age [36–38]. In fact, there has been recent interest in applying a modified version of the ITB technique to skeletally mature adolescents [80].

There are limited studies thus far comparing operative techniques. Regarding physeal-sparing techniques, biomechanical cadaveric studies by Kennedy et al. and Trentacosta et al. suggest that both techniques improve anterior translation [33, 34]. ITB techniques, however, may do so to a greater extent and provide better rotational control than AE techniques. Knapik et al. performed a systematic review to compare clinical results between these two techniques, reporting on 14 studies including 443 skeletally immature patients [39]. While they found no difference in the ultimate PROs obtained, retear rates were higher in AE than ITB patients, though not to a statistically significant degree (7.9% vs 3.6%, $p = 0.52$). RTS rates were higher after ITB reconstructions than AE reconstructions, at 97% ant 87% respectively ($p < 0.001$), and limb length discrepancies ≥ 10 mm were also significantly higher after all-epiphyseal techniques (4.3% vs 0.8%, $p = 0.02$).

Physeal-sparing techniques have been compared to partial transphyseal and transphyseal techniques in a limited number of studies. A cohort study by Patel et al. comparing 162 patients after AE ACLR and 843 patients after transphyseal ACLR found no difference in retear rates [50]. However, retear rates were significantly higher and return to sport rates significantly lower after partial transphyseal techniques than after AE or transphyseal techniques in a study by Cordasco et al. Additional studies, including systematic reviews by Buckle et al. and Pagliazzi et al. have reported globally comparable results of physeal-sparing techniques in general to those of physeal-respecting techniques [50, 69, 81••, 82]. PROs of all techniques are relatively high, compared with normative values in children, with Lysholm and IKDC scores all > 92, also paired with high rates of activity (average Tegner score > 6). In one study, physeal-sparing techniques demonstrated less post-operative laxity, though not necessarily to a clinically significant extent [81••]. There was no difference in retear rates nor in growth disturbances across the groups [69, 81••].

Larger multicenter registry studies are underway. The Pediatric ACL Initiative (PAMI) was started by the European Society of Sports Traumatology, Knee & Arthroscopy in 2018. They have thus far reported on international acceptance and consolidation of the project, as well as on the epidemiology of the first 100 patients enrolled [83]. In the USA, the Pediatric ACL: Understanding Treatment Options (PLUTO) study group set out to follow skeletally immature patients treated at 10 hospitals for ACL tears for 5–10 years. Two-year outcome data on 742 patients who underwent either physeal-sparing or physeal respecting ACL reconstructions of a mean age of 12.9 ± 1.9 years old were recently presented at the Pediatric Research in Sports Medicine Annual Meeting [84••]. Pedi-IKDC (available in approximately 75%) were not different across surgical technique or graft types. Graft rupture was seen in 7% overall, with lower rates in the ITB (3%) and AE (3%) techniques as compared PTP (8%) and transphyseal (10%) techniques.

Adjunctive Procedures and Other Measures Designed to Reduce Secondary ACL Injuries

Given the relatively high retear rates after pediatric and adolescent ACL reconstructions, much consideration has been given to how to reduce the rate of secondary ACL injuries. Secondary injuries include not only ipsilateral ACL graft ruptures but contralateral ACL injuries as well. Several surgical adjuncts and components of postoperative rehabilitation should be considered in addition to well-performed physeal-sparing or physeal-respecting ACL reconstruction.

Correcting Genu Valgus with Guided Growth

A subset of patients with ACL injuries have underlying coronal or sagittal plane angular deformities, which may be noted pre-operatively. Coronal plane malalignment, most notably genu valgus, may have contributed to the index injury and may put patients at an increased risk for graft rupture after ACL reconstruction [85, 86]. Genu valgus can be structural or dynamic in nature, though some patients present with both forms [85]. While dynamic valgus can be addressed during postoperative rehabilitation, structural valgus is a mechanical constant and may worsen with continued growth.

Structural genu valgus is best measured on hip-to-ankle radiographs, using the mechanical axis deviation, angular axis deviation, lateral distal femoral angle, or medial proximal tibial angle to determine the source of the malalignment. While correction of genu valgus in adults requires an osteotomy, guided growth procedures which are much less invasive can be used in skeletally immature children and adolescents, typically in the same operative setting as an ACL reconstruction. Two forms of the technique are commonly used today. A hemiepiphysiodesis plate may be placed in spanning fashion over the medial distal femoral physis, with short screws proximal and distal to the physis. Alternatively, a long, large-diameter threaded hemiepiphyiodesis screw may be placed across the medial distal femoral physis, usually from the lateral diaphyseal-metaphyseal region over a cannulated guidewire. Both techniques, which each have their own advantages, present minimal to no interference with common ACLR techniques. While there is also minimal additional operative time, depending on the remaining growth of the patient, secondary removal of implant surgery may be required to prevent overcorrection of coronal plane malalignment. Thus, strict monitoring with hip-to-ankle radiographs every 4 to 6 months is required to monitor alignment correction over time. The implants are typically removed after slight overcorrection in those with significant growth remaining, as rebound growth is not uncommon.

While used anecdotally, there is little literature to date on guided growth used in conjunction with ACL reconstruction. Fabricant et al. have reported on 7 patients with guided growth performed at the time of ACLR [86]. They provided a matched cohort of patients undergoing guided growth alone and found the efficacy of the technique to be the same in both settings. O'Brien et al. similarly reported on 8 patients after ACLR and guided growth, demonstrating a mean correction of 0.4°/month to near neutral alignment for all knees [87]. They reported a retear in one patient (13%) though have no comparison for retear rates in similarly at risk patients. Ellsworth et al. looked more broadly at patients treated with guided growth and other knee pathologies, predominately patellar instability [88]. However, they reported adequate deformity correction in the 5 patients undergoing concomitant ACLR.

Lateral Extra-articular Procedures

Lateral extra-articular procedures (LEAPs) have been increasingly recognized as important adjuncts to ACL reconstructions in high-risk patients, including children and adolescents. The most commonly utilized LEAPs include anterolateral ligament reconstruction (ALLR) and lateral extra-articular tenodesis (LET), multiple variants of which have been reported [89–91]. Minor modifications to the techniques are sometimes required for skeletally immature patients, including confirming that the insertion of the graft on the femur is distal to the physis and aiming any drilling away from it. Additionally, an onlay technique using suture anchors or blind socket techniques using tenodesis screws may be preferred to transphyseal tunnels with interference screws or suspensory fixation, given technical challenges in avoiding the physis. Indications for LEAPs continue to evolve but often include young age, hyperlaxity, knee recurvatum (e.g., > 10°), a high-grade pivot-shift test and a desire to return to cutting, pivoting, collision or contact sports [90, 92, 93].

Cadaveric studies, including those with pediatric specimens, have demonstrated reduced anterior tibial translation and improved rotational stability with LEAPs [33, 94–96]. This finding is most consistent with LET techniques as well as with ITB ACL reconstructions, which inherently include an extra-articular tenodesis similar to that of an ALLR [33, 94, 97]. The additional rotational control provided by the extra-articular component of the ITB ACL reconstruction may, in fact, be an important contributing factor to the low retear rates of that technique. Improved anteroposterior and rotational stability were also demonstrated in vivo after ACL reconstruction with LET in a cohort study by Perelli et al. using KT-1000 and KiRA testing, respectively [98•].

Few studies have thus far reported clinical results of ACL reconstructions with LEAPs in skeletally immature patients. Green et al. report no graft failures at an average of 3.4 years after AE or transphyseal quadriceps ACL reconstruction with LET in 49 patients of an average of 14.2 ± 1 years old [99]. A systematic review by Carrozzo et al. reported an average retear rate of 4.7% across 5 studies using varying ACL reconstruction techniques in conjunction with an LET in skeletally immature patients [100••]. However, neither group provides a comparative cohort of ACLR without LEAP. Perelli et al. did compare PTP hamstring ACL reconstructions with and without LETs in 66 patients and found the cohort with LETs to have a significantly lower cumulative failure rate (6.3% vs 14.7%, $p = 0.021$) than those with isolated ACL reconstructions [98•].

Other notable studies not exclusive to skeletally immature patients have included broader ACLR populations extending to the adolescent age group, but have importantly demonstrated lower retear rates in LEAP patients than those without LEAP [93, 101]. In the STABILITY Trial, retear rates after hamstring ACLR with LET were 4%, compared to 11% for ACLR in isolation [101]. The SANTI group similarly reported retear rates after hamstring ACLR with ALL to be 4%, compared to 11% in isolated hamstring ACLR and 17% in BTB ACLR [93]. These trends held true across a systematic review with meta-analysis by Na et al. of 20 studies, including 11 randomized controlled trials [102]. Reoperation rates for secondary meniscal tears were also found to be lower, at 2% in patients after ACLR and LEAP, compared to 10% in patients with an isolated ACLR [103]. These studies and others further suggest low complication rates, strong patient reported outcomes and high rates of return-to-sports after ACLR with LEAP, though not necessarily superior to those of ACLR alone [93, 100••, 101, 104•]. One notable risk of LEAPs is over-constraint of the lateral compartment. However, biomechanical data has been mixed in this regard[33, 105], and few if any long-term studies are available of modern LEAP techniques, which tension the graft in neutral rather than in external rotation.

Rigorous Assessment of Readiness for Return to Sports

Many pediatric and adolescent patients plan to return to sports after their ACL reconstruction, yet young age and return to sport are independent risk factors for subsequent ACL injury. Second ACL injuries can be in the form of ipsilateral graft failure or contralateral ACL tears. Returning to cutting and pivoting activities can increase the risk of graft failure by a factor of 3.9 and that of contralateral tears by a factor of 5 [106].

Many of these injuries occur shortly after returning to play, suggesting that they perhaps were not yet ready for the rigorous demands of their sports. Time, as well as physical and psychological readiness, likely contribute to the overall success of returning to sports. Dekker et al. found time to return to sport to be a significant predictor of a second ACL injury, with a 13% risk reduction per month [107]. Grindem et al. similarly found a 51% reduction of retears per month up to 9 months post-operatively and Beischer et al. found a HR of 6.7 for a second ACL injury in those who returned to sports before as compared to after 9 months post-operatively [108, 109].

While time itself may be a necessity for graft incorporation and maturation, it may also allow for sufficient physical recovery and rehabilitation before returning to sports. Benchmarks for appropriate physical recovery should include knee strength and stability as well as neuromuscular (i.e., balance, proprioception, and movement quality) metrics. There is significant variation in the tests and associated cut-offs used in return-to-sport testing for pediatric patients across the literature [110]. In general, testing should be developmentally appropriate for children and adolescents, and the benchmarks used for comparison should be critically analyzed [111]. Many protocols compare the injured and uninjured legs. However, even healthy uninjured pediatric athletes have significant baseline limb asymmetries [112]. Even assuming limb symmetry prior to injury, the non-operative leg becomes deconditioned after surgery and may not be an appropriate baseline [113]. Comparing metrics of the operative limb after surgery to metrics of the non-operative limb obtained pre-operatively may be more appropriate. Age- and sex-based normative data for some common return-to-sport tests is also available, but somewhat limited at this time [114, 115].

In addition to physical readiness, psychological readiness has been increasingly recognized as an important component of returning to sports. Components of emotional response, risk appraisal and confidence in the operative knee correlate to varying extents with physical readiness to return to play as well as to actual return to play rates [116, 117•, 118]. A cohort study by Webster et al. found that only 25% of pediatric and adolescents failing to return to sport did so due to poor knee function. Thirty percent cited life circumstances and another 25% cited psychological reasons for their failure to return to play [117•]. A systematic review of 28 studies similarly noted up to 65% of patients citing psychological reasons as the cause for their failure to RTS [119]. To that end, the ACL-RSI was developed to assess a patient's psychological readiness to return to sport and has been validated in young athletes [117•, 120]. Further work is needed to understand how to best identify and help patients with low psychological readiness, but who still maintain a desire to return to sports.

In summary, return to sports should be considered a continuum, acknowledging that the risk of retear decreases with increasing time, strength, improved biomechanics, and psychological readiness. These factors act in concert but there are no definitive cut-offs which guarantee a successful return to sport. While work is still needed to determine the optimal return-to-sport testing for pediatric and adolescent patients, it is clear that some form of testing is beneficial to evaluate readiness and risk associated with resuming high risk sports. A number of groups have reported on decreased retear rates for those who met versus those who did not meet return-to-play criteria, on the order 5–10% versus 30–40% [108, 121].

Bracing with Return to Sports

Functional bracing after ACL reconstruction is somewhat controversial. Clinicians are divided in that 50% of members of the Pediatric Research in Sports Medicine (PRiSM) Society recommend the use of a functional ACL brace after ACL reconstruction, while the other 50% do not [122]. Patients are similarly divided. Some have additional confidence or a sense of security with the ACL brace on, while others feel inhibited. However, functional braces do serve as a reminder to young athletes and those around them of their recent injury and extended rehabilitation.

Biomechanical studies are conflicted in terms of the overall benefits. Functional bracing does decrease anterior tibial translation by around 30–40% without peri-articular muscle contractions [123]. In conjunction with muscle activation, it decreased between 70 and 80% of anterior tibial translation. However, bracing may slow hamstring reaction times and prolonged brace use may lead to decreases in quadriceps strength, especially in mid-flexion [123, 124].

There are conflicting reports on if functional braces provide control of varus/valgus moments [125, 126]. However, bracing does prevent hyperextension, though some argue patients should be retrained during postoperative rehabilitation to avoid hyperextension without the brace [127]. Additionally, there is conflicting data on whether bracing improves proprioception [124, 128, 129]. In terms of functional testing, bracing does not appear to affect most tests, including single-leg hop, landing accuracy, jumping heights and agility testing [124, 128, 130]. However, bracing also does not decrease kinematic asymmetries between the operative and non-operative knees and can affect the kinematics of the non-operative knee [126, 131].

It is unclear if bracing changes patient outcomes. No differences were found in multiple studies on subjective outcome scores, including IKDC, Tegner, Cincinnati Knee Injury and Osteoarthritis Outcome Score or VAS [130, 132]. Given that graft failures after ACLR are relatively rare, most studies have been underpowered to show a statistical difference between braced and unbraced patients [133]. In perhaps the most rigorous study to date, McDevitt et al. reported on 99 patients in military service academies randomized to brace versus no brace for a year after ACL reconstruction [130]. There was no difference in knee stability, range of motion, functional testing or patient reported outcomes scores between the two groups. There were 2 (4%) retears in the braced cohort as compared to 3 (6%) retears in the unbraced cohort.

While the study by McDevitt et al. included patients with high athletic demands, it did not assess bracing in skeletally immature children. To that end, Perrone et al. compared 142 American children and adolescents who were braced during cutting or pivoting sports for 2 years after surgery to 140

Australian children and adolescents who were not braced for return to sports [134]. Retear rates were significantly lower in the braced cohort, at 10% as compared to 21% in the unbraced cohort. This is despite only 54% of the patients in the braced cohort were in fact wearing the brace at the time of graft failure. It should be noted that only 63% of patients in the braced cohort returned to strenuous sport as compared to 88% in the unbraced cohort. While this study is promising regarding the effect of the brace, it is limited by differences in patient populations, surgical techniques and rehabilitation between cohorts.

Conclusion

Anterior cruciate ligament tears in skeletally immature children and adolescents present a unique challenge to orthopedic surgeons. While many internationally recognized experts feel there is an important role for non-operative treatment, the challenge remains in identifying optimal candidates, given the well-established higher risks of persistent knee instability, meniscal, and chondral damage following non-operative methods, when compared to operative treatment. The skeletal age of a patient should be carefully considered when choosing a pediatric reconstruction technique. Prepubescent patients with more than 2 years of growth remaining typically undergo physeal-sparing techniques (ITB or all-epiphyseal), while pubescent adolescents with open growth plates and 1–2 years of growth remaining undergo physeal-respecting (partial transphyseal or transphyseal) techniques. Though growth disturbances are rare with contemporary techniques, early identification allows for appropriate treatment. Thus, monitoring such patients radiographically until skeletal maturity to assess any limb length differences or angular malalignment is a critical component to post-operative care. Patient-reported outcomes and return-to-sport rates are quite favorable after ACL reconstruction across these younger populations, though retear rates are higher than in adults. They also appear to be higher in the transphyseal reconstruction population than physeal-sparing reconstruction population. Adjunctive treatment measures, including guided growth, lateral extra-articular procedures, evolving rehabilitation and prevention strategies, and return-to-sport testing, may lower retear rates but further research if warrant to establish a more robust algorithmic approach for this rapidly expanding sub-population of patients with ACL tears.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of Interest Benton E. Heyworth, MD has textbook related royalties or licenses from Springer Science & Business Media. He has also received consulting fees from Kairos Surgical, Arthrex Inc., and Imagen Technologies. He also holds stock in Imagen Technologies. He was previously a Board of Directors Member of the Pediatric Research in Sports Medicine Society and a previous committee member and/or chair for the Pediatric Orthopaedic Society of North America. Elise C. Bixby, MD has received grant funding from Arthrex as well as educational support from Smith + Nephew Inc. and Peerless Surgical Inc. She is a member of the Patellofemoral Instability Research Interest Group.

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- •• Of major importance

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