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State of the Art Review

Graft choices for paediatric anterior cruciate ligament reconstruction: State of the art

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ABSTRACT

The paediatric population is at particularly high risk for anterior cruciate ligament (ACL) injuries due to high rates of sports participation. Other risk factors for ACL injuries in children include but are not limited to being female, generalised ligamentous laxity, a high body mass index (BMI), and poor neuromuscular control. ACL reconstruction (ACLR) is commonly done to treat ACL injuries and allow for return to sports and daily activities. ACL repair is another option with ongoing techniques being developed. The high rates of graft failure in children reported in recent publications on ACL repair are very concerning. Special consideration must be taken in ACLR in the skeletally immature patient due to the risk of growth-related complications, such as limb deformity or growth arrest, that can arise from drilling across or disrupting the physis. Graft choices for paediatric ACLR include iliotibial band (ITB) over the top and over the front, hamstring autograft, bone patellar tendon bone (BTB) autograft, quadriceps tendon autograft, and allograft. Factors for each graft choice to consider include graft size, graft failure rates, donor site morbidity, requirement for bony tunnels, the post-op rehabilitation process, and return to sport outcomes. Each graft has its benefits and disadvantages for the individual patient, depending on age, skeletal maturity, and goals for recovery. Lateral extra-articular tenodesis (LET) is another option to consider with paediatric ACLR because LET has been shown to decrease the re-rupture rate in adult ACLR. After surgery, patient follow-up until at least the growth plates are closed is important. This article aims to provide an overview and comparison of the various graft types to aid in the graft choice decision making process for paediatric ACLR.

Introduction

While a person is a minor until they are 18 years old, the US Federal Drug Administration (FDA) definition of a “pediatric patient” is a person aged 21 or younger at the time of their diagnosis or treatment. This higher upper age limit is set particularly for advisory panels and the regulation of medical devices used in the paediatric population. Children are between 2 years and 12 years old, and adolescents are between 12 years and 21 years old [1]. However, when dealing with surgical cases for anterior cruciate ligament (ACL) injuries in the paediatric population, it is more effective to distinguish between closed physis (growth plates) and open physis. The skeletal age of the patient allows an estimate of the growth remaining at the level of the knee and thus the risk of subsequent postoperative malalignment or leg length discrepancy [2]. It was also found that Tanner staging is unreliable when used as a method to guide decision-making for surgery in skeletally immature patients [3].

Conservative treatments are an option for treating ACL injuries in the paediatric population [4]. Non-operative treatments include physical therapy with exercises that focus on improving neuromuscular control, knee stability, gait, knee extension, quadriceps activation, and pivoting. These exercises are performed at different phases of recovery [5]. With adherence to quality rehabilitation, conservative treatments can be effective for some paediatric patients; however, they must be closely monitored for future instability and/or meniscal tears. However, if knee

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stability is not fully recovered through rehabilitation, non-operative treatments present risks of secondary damage, including meniscal tears and cartilage damage, due to persistent knee instability. Return to sport may also be delayed [4].

Surgical management with ACL reconstruction (ACLR) is another option for treatment of ACL injuries. The procedure often involves drilling near or across the physis in order to create tunnels in the femur and tibia to hold the new graft in place. This presents with risks of growth and axis abnormalities in paediatric patients because these patients may have open physis [2]. These risks associated with ACLR should be considered against the risks of conservative treatments. Despite the risks with ACL reconstruction, ACLR offers higher rates of return to sports than operative treatments [6]. Early ACLR compared to delayed ACLR or non-operative treatment results in fewer meniscus tears and cartilage damage [7]. Ultimately, the decision to pursue conservative treatment or ACLR depends on the individual patient with consideration of the injury and goals with regards to return to sport.

There are multiple surgical techniques using a variety of grafts for paediatric ACL reconstruction. Techniques can be transphyseal, all epiphyseal, or extraphyseal (over the top of the femur and over the front of the tibia without bone tunnels), or a combination thereof. Graft options include autograft and allograft. The latter is associated with a re-rupture rate of two to three times higher incidence, so we generally recommend avoiding allograft tissue for isolated ACL reconstruction, especially in the paediatric population who are at the highest risk due to their age and activity level [8,9]. We also recommend avoiding ACL repair in view of the high failure rates, including very high rates in paediatric patients reported in a recently published study [10].

When drilling across the physis, the concern is growth arrest in a skeletally immature patient. In a sheep model, it has been shown that growth plate lesions on the central tibial tunnel with soft tissue grafts in the tunnels show no growth disturbance. However, on the peripheral femur, posterolateral growth plate injuries with empty tunnels led to shortening, valgus deformity, and flexion deformity [11]. In animal studies, it has been shown that an injury to 7–9% of the growth plate can lead to major and permanent growth disturbances [12]. However, with tunnels less than 9 mm, studies in humans have shown no major risk of growth disturbance [13]. An 8-mm drill hole in a 12-year-old female will injure 3–4% of the growth plate, and Janarv et al. found no effect on growth with drill hole area less than 4–5% of the growth plate [14]. It is also important that surgeons do not use hardware, synthetics or bone crossing the physis in order to avoid growth-related complications in the paediatric patient [15].

Autograft options include iliotibial band as described by Micheli [16, 17], hamstring tendons [18–20], patellar tendon [21], and quadriceps tendon [22]. There is no ideal graft for paediatric patients in general, and each has pros and cons. It is important to understand that there is no ideal graft for a given patient, but rather there are choices, and we attempt to illustrate the various options based on the latest data and science, as well as our collective experience.

Geographic differences in ACL reconstruction

Little has been documented in the literature regarding geographic differences in ACL reconstruction, especially in paediatric patients. In adults, a study with registries from six countries worldwide found that the mechanism in which an ACL injury occurs and patient demographics were very similar. However, the United States of America differed from European countries in that allografts were used in significantly more patients. Furthermore, Luxembourg and the US used an interference screw for femoral fixation more, while European countries used suspensory fixation [23]. A survey with surgeons from 57 different countries worldwide further supports the higher rate of allograft use in the US compared to other countries. Additionally, hamstring autografts were used more often outside of North America as compared to the bone patellar tendon bone (BPTB) graft. Despite BPTB grafts having the lowest graft failure rate, hamstring autografts may be preferred because of the possible increased risk of complications associated with BPTB grafts. Furthermore, North American surgeons do not use the double bundle technique as much as surgeons from other countries [24]. Outcomes are generally the same worldwide with similar revision rates [23]. One study found greater quadriceps weakness when comparing the surgical limb with the healthy limb in the US compared to Europe [25]. Many of these findings and differences do not have concrete explanations but rather is dependent on the relatively small population studied. Given the difference in rates of using various grafts, more studies should be done to ascertain the geographic differences, especially in paediatric patients, to better inform the process of graft choice in paediatric ACLR.

Box 1
Key Articles

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Box 2
Validated outcome measures and classifications

- Return to sport rate
- Growth-related complications
- Graft failure or surgery revision rate
- Tegner Activity Scale
- Marx Activity Rating Scale
- Pedi-International Knee Documentation Committee (IKDC) Subjective Knee Form Score

Box 3
Key issues of patient selection

- Paediatric patients may be skeletally immature. This can result in growth-related complications, such as growth arrest or limb deformity, with paediatric ACLR due to disruption of the physis.
- The patients' level of skeletal maturity and desired activity level should be considered when choosing graft type.
- Paediatric patients must be willing and be able to undergo postoperative rehabilitation for best outcomes.

Graft choices

Iliotibial band over the top and over the front

With traditional adult ACL reconstruction (ACLR), creation of tunnels and fixation across the physis introduces the possibility of growth disturbance for paediatric patients who have growth remaining. Micheli developed the technique of using the iliotibial band (ITB) autograft over the top of the lateral femoral condyle and over the front of the tibia, which does not require bony tunnels [16,17]. This combined intra-articular/extra-articular physeal-sparing technique with ITB autograft is recommended for very skeletally immature patients (Tanner Stages 1 and 2), where non-operative treatments have failed. These patients often have problems with pivoting and are at higher risk of meniscal or chondral injury. The surgery is recommended for prepubescent patients, with skeletal age confirmed with a hand and wrist radiograph. Tanner Stage 1 or 2, as confirmed by a physician, corresponds to less than or equal to 12 years old for males and less than or equal to 11 years old for females. Once the patient has entered the pubescent stage with growth, an anatomical technique with tunnels can be performed, rather than the ITB autograft. This stage corresponds with Tanner Stage $\geq$3, with males between 13 and 16 years old and females between 12 and 14 years old. For these very young patients, they must also be found to be willing and able to complete postoperative rehabilitation [26].

In a recent article, Sugimoto et al. examined the outcomes of 38 paediatric patients following ACL reconstruction with ITB using 3-dimensional (3D) motion analysis. All of the patients had at least 2 years of growth left after surgery, and the mean time between the surgery to kinematic and kinetic tests done was 5.98 years. The participants completed the drop vertical jump manoeuvre and vertical simple-limb hop tests. The drop vertical jump demonstrated that the mean peak normalised ground-reaction force (GRF) at landing was not significantly different between the surgical and non-surgical limb. Similarly, the vertical single-limb hop test revealed that there was no significant difference between the surgical and non-surgical knee for the mean normalised GRF at landing and mean peak vertical jump height. These results demonstrate that for most paediatric patients after ITB ACLR, the function of the surgical knee is restored to a level almost equivalent to the contralateral knee after a year [27].

The surgical technique is described subsequently. A lateral incision is made over the distal iliotibial band. A 1-cm strip of the iliotibial band is dissected free and detached approximately 15–18 cm from the distal end of the lateral femoral condyle. The iliotibial band is left attached distally and dissection is performed distally to separate the iliotibial band from the joint capsule and from the lateral patellar retinaculum. The free proximal end of the iliotibial band is sutured for subsequent graft passage. Arthroscopy of the knee is performed and the torn anterior cruciate ligament fibres are excised. A notchplasty not performed to avoid iatrogenic injury to the perichondrial ring of the distal femoral physis, which is in close proximity to the over-the-top position. The free end of the iliotibial band graft is brought from the over-the-top position and through the knee arthroscopically with use of a clamp. A second incision of approximately 4–5 cm is made over the proximal medial aspect of the tibia. A curved clamp is placed from this incision into the joint under the intermeniscal ligament. A small groove is made in the anterior proximal tibial epiphysis under the intermeniscal ligament with use of a shaver to bring the tibial graft placement more posterior. The free end of the graft is then brought through the joint, under the intermeniscal ligament and out the medial tibial incision. The graft is fixed on the femoral side through the lateral incision with the knee at 90° of flexion with use of mattress sutures to the lateral femoral condyle periosteum at the insertion of the lateral intermuscular septum to affect an extra-articular reconstruction. The tibial side is then fixed through the medial incision with the knee flexed 20° and tension applied to the graft and the graft is sutured to the periosteum with multiple figure of eight non-absorbable mattress sutures [17].

Hamstring autograft

Hamstring grafts do have advantages that account for its popularity in young athletes. ACL reconstruction with a hamstring graft has less quadriceps inhibition postoperatively and avoids the risk of patella fracture that comes with bone tendon bone (BTB) grafts [28]. With BTB, there is also a higher prevalence of anterior knee pain and kneeling pain [29]. Hamstring autograft has been used extensively for skeletally immature patients with a variety of techniques including transphyseal, all-epiphyseal and also without a tunnel on the femur, fixing the graft in the “over the top” of the lateral femoral condyle position. All of these techniques have published data to support their use [18–20], and in general we prefer a transphyseal technique to ensure that the graft is placed in the optimal position most reliably. The preferred graft for the young ACL patient is the 4 stranded semitendinosus graft or a 6–8 stranded semitendinosus/gracilis if a longer graft is needed. If possible, consider using a single tendon because it leads to increased deep flexion strength, increased internal rotation strength, and acts as a medial dynamic stabilizer [30–32].

One of us has published a series of four cases of growth abnormalities after trans-physeal ACL reconstruction with hamstring autograft [33]. Four patients that underwent surgery presented with growth retardation or premature growth plate closure on average 11 months after the surgery. Two patients developed asymptomatic tibial recurvatum due to closure of the tibial apophysis as confirmed by a bilateral CT scan. One possible explanation for the tibial apophyseal growth arrest is that the patients experienced rapid growth spurts. This could result in tenoepiphysiodesis, where the graft tension across the physis leads to the growth arrest. The other two patients developed asymptomatic valgus deformity as demonstrated with 3D growth plate mapping MRI. The authors speculated that growth was impacted in these cases because the femoral sockets created through an anteromedial portal with an oblique trajectory resulted in injury to a greater cross-sectional area of the physis [33]. Still, the prevalence of these growth disturbances are unusual in ALCR. In a meta-analysis by Wong et al., only 58 out of 1,329 paediatric ACL reconstructions (4.4%) resulted in growth disturbances, and 16 of these 58 cases (27.6%) required corrective surgeries. Of these growth disturbances cases, abnormal valgus consisted of 14 patients (1.1% of total cases) and recurvatum was seen in 3 patients (0.2% of total cases) [34].

To prevent growth arrests following transphyseal ACL reconstruction with hamstring autograft, the authors recommend the following considerations. To avoid tibial recurvatum, a vertical tunnel not too anterior to the ACL footprint can be used to reduce the tension on the graft. Patients should be followed for hyperextension in the operative leg 6 and 12 months post-op as early signs of tibial recurvatum related to tibial tubercle apophyseal growth arrest. To prevent genu valgum, it is important to consider both the trajectory and size of the reamer used in order to reduce the amount of cross-sectional area of the physis resected by tunnel creation. Other considerations to prevent growth arrest include hardware or bone plug placement near the physis, drilling too close to the physis, and extensive periosteal stripping during graft harvest. The authors also recommend thorough pre-op evaluation, including long leg AP and lateral hip-to-ankle films. These radiographs should also be continued 6- and 12-months post-op or every 6 months until growth plates fused to monitor proper lower limb alignment [33].

Lo et al. has described hamstring autograft with a combined transtibial and extraphyseal (or "over the top" technique) on the femur [20]. For this technique, grafts are released proximally and all are kept in continuity at their distal insertions. The Kennedy ligament augmentation device (Kennedy-LAD) was incorporated for some cases into a composite graft and secured proximally but not distally. However, Kennedy-LAD is no longer used, especially in skeletally immature patients, ever since its discontinuation in 2009.

Despite claims of newer techniques and procedures for the hamstring graft ACL reconstruction potentially leading to lower revision rates, Murgier et al. found that traditional 4-stranded semitendinosus hamstring grafts and multiple strand hamstring grafts have a very similar failure rate indicating that a thicker hamstring graft does not result in a lower failure rate. They also found that BTB grafts have a significantly lower failure rate of 0% in females than hamstring grafts which had a 5.1% failure rate. This was a study of 991 patients less than or 20 years of age and were followed for 2–5 years after surgery [35]. A study also examined return to preinjury activity levels using the New Zealand registry. Using a preoperative Marx score of 13 as the high activity threshold, it was found that at1 year, 17.2% of BTB graft operations and 9.3% hamstring graft operations had a Marx score of 13 or greater. At 2-year post-op these rates were 23.3% and 13.3% for BTB and hamstring respectively [36]. Males and patients of a younger age had a higher return to activity. This may contribute to the higher rates of contralateral ACL injury in BTB graft ACL reconstructions.

An all-epiphyseal technique has been reported by several authors and has the theoretical advantage of avoiding the growth plates altogether [19,37,38]. However, in practice, the tunnels are created in very close proximity to the physis and the risk of physeal injury is not insignificant with this technique, with complications and re-operation rates that limit the theoretical advantages of the technique in our opinion [39–42].

Additionally, living donor hamstring allograft has been studied in children as well [39]. In 100 children with a median age of 14 years old, 79 hamstring grafts were donated by the father and 21 by the mother. The median hamstring graft diameter was 7.5 mm and a 4-strand graft was used in 86 cases and a 2-strand raft was used in 14 cases. Thirty-nine of the paediatric patients had open growth plates, 22 had closing growth plates, and 39 had closed growth plates. Clinical outcomes with this cohort were associated with excellent subjective outcomes, including good ligament stability, a high rate of return to sports, as well as absence of significant difference in radiographic leg length over 2 years. However, the graft rupture rate was 24% in males and 16% in females. In addition, positive family history of ACL rupture increased the risk of subsequent injury [43].

Bone patellar tendon bone autograft

For patients with open physis that are near closure and therefore have minimal growth remaining, bone-tendon-bone autograft is an excellent option, particularly in view of the lower re-rupture rate associated with this graft [36,44]. Most females 13 years of age and over (especially if postmenarchal) as well as males 15 years of age and older have relatively minimal growth remaining and will not develop a clinically meaningful deformity following BTB ACL reconstruction [45]. However, for patients with significant growth remaining that could lead to a centimetre or more in the distal femur or proximal tibia, BTB should be avoided since the bone plugs and fixation crossing the physis will definitely cause a growth arrest and subsequent deformity.

For BTB, it is important to exclude skeletally immature patients with more than a year of growth remaining. In New Zealand, 54% of the ACL injuries occur in rugby, football, and net ball. Thus, a majority of the athletes injured participate in pivoting sports. There is a slow increase in BTB use in New Zealand, but hamstring tendon is still used for 60% of ACL reconstructions. In terms of graft survival, patellar tendon has a higher cumulative survival rate with respect to re-tear, even at year 1. Based on the New Zealand ACL registry, there is a 2.7% failure rate when using BTB tendon vs. 12.4% failure rate in hamstring grafts in patients less than 20 years old. This difference persists for patients 20–24 years old, and in patients greater than 25 years of age. Across many studies, hamstring tendons have been shown to have revision rates that are significantly higher than for BTB [46–48].

Quadriceps tendon autograft

Quadriceps autograft has received increased attention over the past decade as an option for ACL reconstruction in the skeletally immature patient population [22,38,49,50]. Potential advantages include the size and strength of the graft as well as the avoidance of bone plugs that can affect growth as well as improved kneeling pain. When using the quadriceps, it is important for surgeons to avoid inadvertent release of the rectus tendon from the rest of the quadriceps tendon complex. As well, careful closure of the defect is of the utmost importance when using a quadriceps tendon graft [51]. The data on this graft for skeletally immature patients remain relatively short-term compared to the other options.

Lateral extra-articular surgery

Lastly, in adults, multiple studies have shown that lateral extra-articular tenodesis (LET) combined with ACLR can reduce re-rupture rate in high-risk patients [52–54]. Patients with ACLR and LET were also found to have an improved pivot shift as compared to patients with ACLR alone. More large-scale studies are needed to determine if LET significantly increases return to sport and patient reported outcome measures (PROMs) [54]. Depending on graft choice and the specific patient factors, lateral extra-articular surgery with either ITB or anterolateral ligament reconstruction can be considered. The European registry, Paediatric Anterior Cruciate Ligament Monitoring Initiative (PAMI), showed graft selection for acute ACL reconstructions with open growth plates to be majority semitendinosus and/or gracilis (72%) and a minority quadriceps tendon (28%). Extra-articular tenodesis was performed in 40% of those patients. For delayed ACL reconstructions 44% used quadriceps tendon, 39% semitendinosus and/or gracilis, and 17% patellar tendon. Extra-articular tenodesis were performed in 33% of those patients [55].

Recent studies have demonstrated that the lower graft failure rate associated with ACLR and LET combined is also seen in skeletally immature patients [56,57]. Additionally, Monaco et al. demonstrated that ACLR and LET combined resulted in better laxity and knee stability as compared to ACLR alone. PROMs or other complications did not differ between patients with ACLR and LET and patients with ACLR alone [57]. When performing lateral extra-articular surgery, it is important to respect the growth plates as well. One technique for LET is with iliotibial band autograft and fixed by suture without hardware [58]. Another strategy is a modified Ellison technique, which has been popularised in Australia, where a strip of the iliotibial band is detached distally and is passed under the proximal lateral collateral ligament. It is then reattached distally [59].

Allograft

ACL reconstructions with allografts have a much high failure rate in paediatric patients and should not be used. The Multicentre Orthopaedic Outcomes Network (MOON) consortium found that the odds of tear after allograft ACLR are 4 times as high as the odds of autograft ACLR when adjusted for age [60]. Furthermore, patients 10–19 years old that underwent allograft ACLR had a graft tear rate of 37.5%, which is the highest rate of all age groups [60]. Moreover, Maletis et al. demonstrate that depending on the type of chemical processing of the allografts, soft tissue allografts are at least 4.67 times higher risk of ACL revision compared to BPTB autografts [61].

ACL repair in paediatric patients

ACLR is still the gold standard for ACL injuries, but ACL repair remains a controversial topic. In theory, ACL repair in paediatric patients is an attractive option because there is limited risk to the physes, no donor site morbidity and potentially a more rapid recovery from surgery. Ferretti et al. demonstrated that ACL repair in adults can aid the healing of an acutely injured ACL based on magnetic resonance imaging (MRI) review [62]. A cohort study found advantages of ACL repair compared to ACLR, including increased hamstring strength 6 months after surgery and better Forgotten Joint Score-12 (FJS-12) scores. No differences were found in return to sport or complications, but there was a significantly higher failure rate with ACL repair among younger participants [63]. Other ACL repair techniques are being developed, including arthroscopic ACL repair with an absorbable or an all-suture anchor, which does not require bony tunnels. This technique presented by Turati et al. showed almost all subjects (18/19) return to sport at the same preinjury level. At 2 years following surgery, patients felt their knee was normal and did not complain of instability, and patients that underwent ACL repair had comparable PROMs to patients that underwent ACLR. Unfortunately, 21.1% (4/19) patients re-injured their knee on average 4 years after the ACL repair [64].

Despite the possible benefits of ACL repair, higher failure rates following ACL repair compared to ACLR are also reported in other studies. A recent study with modern arthroscopic techniques showed high failure rates specifically in adolescent patients [10]. Another recent study comparing ACL repair and ACLR found patients 21 years and younger had a 37% failure rate following ACL repair compared to 3.5% in patients older than 21 years of age [65]. Overall, we do not recommend ACL repair particularly in paediatric patients given the high failure rates.

Summary

The graft selection for paediatric cases consists of the quadriceps tendon, hamstring tendon, tractus iliotibialis, allografts, living donor allograft, and patellar tendon, the latter of which should only be used if the growth plates are closed or nearly closed. In a systematic review of mainly U.S. studies, it was found that of all paediatric ACL reconstructions, 79% used hamstring autograft, 8.3% used fresh-frozen allograft, 6.4% used BTB, 5.1% used quadriceps tendon, and 1.1% used live donor allografts. When BTB autograft was used, paediatric patients tended to be older. It was also found that ipsilateral graft failure was significantly greater for patients treated with fresh-frozen allografts (16.2%) than hamstring autografts (7.8%) or BTB autografts (6.2%) [66]. This is further supported by Cruz et al., JBJS 2020, which reveals a significantly higher failure rate of 25.5% vs. 16.6% and 8.5% for allograft vs. hamstring and BTB, respectively, in patients 19 years of age and younger [67]. In a comparative 2019 study by Salem et al., it was found that in female athletes aged 15 to 20, BTB autograft led to fewer graft ruptures than hamstring autograft. Interestingly, this difference was not observed in this study for female athletes aged 21–25 years of age. It was also found that BTB autograft led to significantly increased risk of kneeling pain when compared to hamstring regardless of age [68].

Box 4
Essential features of paediatric ACL reconstruction graft types

- Patient skeletal maturity and desired return to play activity level should be considered when choosing graft type.
- The iliotibial band over the top and over the front technique is for very skeletally immature patients and does not require bony tunnels.
- Hamstring autografts offer an easier recovery with less quadriceps inhibition and decreased risk of patellar fracture as compared to bone patellar tendon bone autografts.
- Bone patellar tendon bone (BPTB) autografts should only be used in patients with near or complete growth plate closure. BPTB autografts offer a lower re-rupture rate.
- Quadriceps tendon autografts provide advantages due to their size and strength, and they do not require bony plugs. More data are needed on quadriceps autografts.
- Lateral extra-articular tenodesis reduces the re-rupture rate in high-risk patients.
- Allografts have high re-rupture rates compared to autografts and should not be used in children.

Box 5
Tips & Tricks

- ACL reconstruction is preferred over ACL repair due to high failure rates associated with ACL repair.
- Transphyseal technique for hamstring autograft is preferred to ensure proper graft placement.
- Follow-up after paediatric ACLR with radiographs is key to prevent limb deformity. Modern limb deformity correction techniques can correct growth complications.

Box 6
Major pitfalls of paediatric ACL reconstruction

- Incomplete preoperative evaluations of skeletal maturity with radiographs
- Performing ACL repair rather than ACL reconstruction
- Inadequate follow-up with the patient post-op with radiographs at least every 6 months until growth plates closed to check for limb alignment abnormalities
- Using allografts
- Drilling more than 7–9% of the growth plate (>9 mm)
- Using hardware, placing bone plugs, or drilling near the physis
- Extensive periosteal stripping during graft harvest

Conclusion

In conclusion, ACL reconstruction in a paediatric or adolescent patient with open physes has relatively low risk for growth disturbance but the risk for subsequent knee injury remains high. There are many options for graft choice, as described above. Common to all grafts and techniques is that no bone or hardware should cross the physis to avoid risking major growth disturbances. Fortunately, even in cases of severe limb deformity following ACL reconstruction, an excellent result can be obtained with modern limb deformity correction techniques [69]. Live donor allografts offer an interesting alternative with excellent recovery but pose ethical and legal issues in many countries. LET may prove to be a useful adjunct in the paediatric population to reduce the historically high re-rupture rates. In general, paediatric ACL reconstruction should be done at spcialised centres and patients should be followed until the growth plates are closed,

Table 1
Summary of graft types for ACLR and treatment options for paediatric ACL injuries.

Graft Type or Treatment Options	Description	Pros	Cons
Non-operative treatment	Physical therapy across four phases, focussing on exercises aimed at improving neuromuscular control, quadriceps activation, knee extension, pivoting, and more.	No surgery is involved. Return to sport at preinjury levels may be possible.	Persistent knee instability may result, leading to increased risk of meniscal tears and articular cartilage damage.
Iliotibial Band over the top and over the front	The iliotibial band (ITB) autograft is attached over the top of the lateral femoral condyle and over the front of the tibia, used for very skeletally immature patients.	No bony tunnels required.	
Hamstring autograft	Graft harvested from hamstring, with multiple techniques, including transphyseal, all-epiphyseal, and also without a tunnel on the femur, fixing the graft in the “over the top” of the lateral femoral condyle position.	Less quadriceps inhibition post operatively and avoids the risk of patella fracture.	Risk of physeal injury and growth disturbances.
Bone patellar tendon bone autograft	Graft harvested from patellar tendon, used for patients with almost closed physes and little growth remaining.	Lowest graft re-tear rate and lowest revision rates.	Risk of patella fracture and more difficult recovery, higher rate of contralateral knee injury and kneeling pain.
Quadriceps tendon autograft	Graft harvested from quadriceps.	Size and strength of the graft, avoidance of bone plugs, improved kneeling pain.	Little data on the use of quadriceps tendon autograft currently.
Lateral Extra-articular Surgery	Part of the iliotibial band (ITB) is repositioned or anterolateral ligament (ALL) is reconstructed.	Lower re-rupture rate, greater knee stability (improved pivot shift), decreases rotational laxity	Adds to recovery and possible increased risk of arthritis.
Allograft	Graft is harvested from a cadaver and chemically processed before being used to reconstruct the ACL.	No donor site morbidity.	High graft re-tear rate.
ACL Repair	The original torn ACL is reattached and repaired.	Limited risk to physes, shorter recovery time, and no risk of donor site morbidity.	Higher failure rates and re-injury rates compared to ACL reconstruction.

at the very least. Additionally, this descriptive review is limited by the scientific value and methodology presented in the included studies. More high-quality studies on paediatric ACL reconstruction are needed in the future to make sound decisions about treatment for paediatric ACL injuries and continually improve outcomes after paediatric ACLR. (see Table 1).

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None

Ethics statement

No study or ethics approval was required for this study.

Conflicts of interest

R.G.M. serves as a Deputy Editor of the Journal of Bone and Joint Surgery and an Associate Editor of Evidence-Based Orthopaedics for the Journal of Bone and Joint Surgery, receives royalties from books published by Springer and Demos Health, and receives equity compensation for seat on science advisory board for MEND Nutrition Inc., outside of the submitted work.

C.F. is a consultant and receives product royalties from Karl Storz and Medacta, and receives fellowship and research support from Arthrex, Zimmer Biomet, and Stryker, outside of the submitted work.

K.E. serves as a consultant for Arthrex, consultant and medical advisory board for Episurf, and editorial board for KSSTA, outside of the submitted work.

A.V. is a shareholder and Director of Forte Health Hospital, outside of the submitted work.

All other authors declare no conflicts of interest.

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