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Anterior cruciate ligament reconstruction in skeletally immature patients

Andrew Pennock [1] · **Michael M. Murphy** [1] · **Mark Wu** [2]

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Abstract The management of pediatric patients with an anterior cruciate ligament (ACL) tear can be a challenging endeavor for physicians, athletic trainers, coaches, and parents alike. In particular, the significant longitudinal growth that arises from the physes about the knee creates a unique set of circumstances that must be considered in this patient population. The purpose of this review is to provide a summary of the most recent current literature for the management of skeletally immature patients with an ACL tear.

Keywords Skeletally immature · Anterior cruciate ligament tear · Transphyseal ACL reconstruction · Iliotibial band reconstruction · All-epiphyseal ACL reconstruction

Introduction

An increased incidence of pediatric anterior cruciate ligament (ACL) injuries has been reported over the last several decades. Management of skeletally immature patients with ACL tears is challenging, given the risks of physeal damage and growth arrest from operative intervention. Historically, these injuries have been treated non-operatively with activity modification and bracing and surgery has been delayed until the patient reaches skeletal maturity. More evidence has shown that delays in surgical reconstruction may increase the likelihood of recurrent instability and subsequent chondral and meniscal pathologies, osteoarthritis, and decreased functional outcome measures [1–6, 7•, 8]. For this reason, surgeons have become more proactive about early surgical stabilization. These can be grouped into physeal sparing reconstruction, partial transphyseal reconstruction, and transphyseal reconstruction. There is currently considerable debate regarding which of these surgical approaches is optimal. Over the last decade, clinical and research interest on this topic has grown dramatically. The purpose of this review is to provide a summary of the most recent current literature for the management of skeletally immature patients with an ACL tear.

Incidence

Pediatric ACL injuries are on the rise. While the exact cause of this trend is unknown, it is likely multifactorial, including increased sports participation, earlier single-sports specialization, year round play, increased injury recognition, and increased utilization of MRI [9, 10]. A study by Sampson et al. reported an average increase of tibial spine fractures and mid-substance ACL tears in children by 1.07 per year and 11.35 per year, respectively, over a 12-year period from 1999 to 2011 [11]. A recent analysis of the Kaiser database between 2005 to 2008 revealed that while the incidence in patients aged 8 to 14 years is low (approximately 1/10,000 lives), this rate gradually increases with age [7•]. A separate analysis that queried a national database showed that from 2007 to 2011 there was a 19 % increase in the number of

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✉ Andrew Pennock
apennock@rchsd.org

Michael M. Murphy
mimurphy@ad.ucsd.edu

Mark Wu
Mark.Wu@childrens.harvard.edu

[1] 3030 Children's Way, 3rd floor, San Diego, CA 92123, USA

[2] Orthopedic Center, 300 Longwood Ave, Fegan, 2nd Floor, Boston, MA 02115, USA

ACL tears diagnosed in the 10- to 14-year age group and a 28 % increase in ACL reconstruction. The study also revealed that diagnosis and reconstruction of pediatric ACL tears were rising at a rate significantly higher than that of adults [12]. These numbers were similar to that seen in a population-based study from New York State that revealed that the rate of ACL reconstructions over the last 20 years has more than doubled in patients aged 3 to 20 years [13].

Natural history

The natural history of the untreated ACL deficient knee in the pediatric population is somewhat controversial, but mounting evidence suggests that delays in reconstruction result in greater meniscus tears and cartilage pathology [6, 14]. Anderson et al. recently showed that delays in surgical reconstruction not only resulted in a significant increase in medial meniscal tears and chondral injuries, but more severe injuries as well. These findings were particularly magnified in patients with any pivoting episodes and in patients returning to pivoting sports prior to reconstruction [6]. Guenther et al. published similar results in a retrospective series where patients who were reconstructed greater than a year after their injury had a higher incidence of medial meniscus tears and were more likely to have a bucket-handle tear [14]. A recent meta-analysis by Ramski et al. extracted data on clinical variables such as symptomatic meniscal tears and post-treatment instability from 11 studies [15]. Data from three of their studies showed that 75 % of patients treated non-operatively had residual instability compared to only 13.6 % of patients that underwent surgery. Data from two studies reported that patients treated non-operatively were over 12 times more likely to tear their medial meniscus to patients having surgery. However, the authors note that the majority of the studies were limited by inconsistent reporting of patient outcomes. While these studies favor early reconstruction, other studies suggest that a non-operative approach can still yield good outcomes. For example, in a prospective series from Oslo, patients under the age of 12 years were recruited into a non-operative pathway after being diagnosed with a complete ACL tear [16]. These patients were enrolled in a supervised rehabilitation program and were allowed to return to unrestricted activities with a custom brace as long as they passed a functional test battery. At a minimum of 2-year follow-up, 78 % of the children had not required an ACL reconstruction and 91 % remained active in pivoting sports. Of note, however, 38 % of patients had decreased their sports activity and 17 % had developed a new meniscus tear [16, 17]. In a study analyzing a single healthcare system database, 71 skeletally immature patients showed that 33 % of pediatric patients were able to be treated successfully non-operatively despite having a documented complete ACL tear. Additionally, the authors did not find an association between time to surgery and meniscal or cartilage injury, which contrasts with previous studies [7•].

ACL and physeal anatomy

Over the last two decades, our understanding of ACL anatomy as it pertains to surgery has evolved, which has affected considerations of graft selection, tunnel placement, and surgical technique. Recently, the pediatric literature has particularly focused on MRI characteristics of the ACL and the epiphyseal dimensions [18–21]. These studies have aimed to further characterize pediatric knee anatomy to determine optimal surgical candidates and techniques for safe ACL reconstruction in skeletally immature patients. An MRI analysis of 132 normal knees spanning the ages of 4 years to 18 years revealed that the ACL diameter grows from 6.5 to 9.8 mm over this period, which may have implications when assessing graft sizes for patients [22•]. Another recent study analyzed 137 knee MRIs performed between 2006 and 2010 in patients aged 3–13 and described a plateau in this ACL growth and notch volume at age 10, with females having smaller intercondylar notch volumes than males [23]. There has been some evidence showing that knees with ACL tears have smaller notch volumes than knees with intact ACLs [24]. A separate MRI analysis was performed evaluating the height of the tibial epiphysis as well as the width of the lateral femoral condyle to better gauge tunnel placement during ACL reconstruction. This study found that the tibial epiphyseal height averaged 15.9 mm and did not vary significantly between the ages of 10 and 14 years. Additionally, the center of the ACL's tibial attachment was consistently near 51 % of the AP diameter. These values may be useful when planning tunnel placement to avoid growth arrest [25•]. A study by Davis et al. reported similar findings with an average tibial epiphyseal height of 15 mm in children and adolescents, along with a femoral condylar width found to be consistently greater than 28 mm, independent of sex [26].

Surgical treatment options

Modern technique options for surgical reconstruction of the skeletally immature ACL include physeal sparing reconstructions (the modified McIntosh technique using the iliotibial band and the all-epiphyseal reconstruction), partial transphyseal reconstruction, or transphyseal reconstruction. The physeal sparing reconstruction using the iliotibial band is a combined extra-articular and intra-articular reconstruction that utilizes no transosseous tunnels and, therefore, minimizes the chances of an iatrogenic physeal injury [27]. It is primarily indicated in Tanner stage I or II patients. The all-epiphyseal reconstruction, also a physeal-sparing approach, consists of drilling femoral and tibial tunnels isolated to the epiphyses. There are several specific variations of the technique that have been developed within this category by Anderson et al., Ganley et al., and Cordasco and Green et al., but they share common principles [28–30]. The transphyseal technique can be performed either as a complete or partial transphyseal reconstruction, which has been performed on patients at Tanner stage I to V [31]. The standard "transphyseal" approach involves drilling across the femoral and tibial physes, then placing a soft tissue graft across the physis to help prevent bony bar formation. Partial transphyseal reconstruction involves drilling across either the femoral or tibial physis and using a physeal-sparing approach on the opposite side. Generally, this involves drilling centrally through the tibial physis, but protecting the femoral physis in some way. Previous animal studies suggests that drilling tunnels greater than 7 % of the cross-sectional area of the distal femoral physis or proximal tibial physis may predispose to bony bar formation and premature physeal closure [32]. To minimize iatrogenic damage to the physis, many surgeons utilize a more vertical tunnel placement which reaming in transphyseal fashion. A recent study showed that femoral tunnels created with an independent drilling technique (outside-in) disrupt a larger area of the distal femoral physis and create more eccentric tunnels compared with a transtibial technique [33]. The theoretic advantage of tranphyseal approaches are that they may allow for a more "anatomic" reconstruction and include intraosseous tunnels that enable better graft incorporation. Before deciding on one of these surgical treatments, it may be important to determine the skeletal maturity of the patient. Historically, the Greulich and Pyle method (GPM) has been the most widely used method of bone age evaluation, which involves referring to a hard copy atlas and adequate training in the technique [34]. To make this process more simple and efficient, Heyworth and colleagues developed a shorthand bone age (SBA) method, which uses a single, univariable criterion of a left hand radiograph for age determination [35•].

Biomechanical evaluations of reconstructive techniques

A small number of biomechanical evaluations have been performed evaluating the various pediatric ACL reconstruction techniques. The first study by Kennedy et al. compared three techniques: the physeal-sparing reconstruction using the iliotibial band, the all-epiphyseal (AE) reconstruction, and a partial transphyseal technique with a tibial tunnel with a graft routed in the "over-the-top" position on the femur [36]. Six cadaveric knees were subjected to different static forces, and displacement and rotation of the tibia in relation to the femur were measured in the intact knee, after ACL tear and after ACL reconstruction. Their results showed that while all three reconstruction techniques restored some stability to the knee, the iliotibial band reconstruction best restored anteroposterior stability and rotational control, although it appeared to slightly over-constrain the knee to rotational forces at some flexion angles [35•]. Another study tested three similar reconstructive techniques using a novel mechanical pivot-shift device (MPSD). Their results differed from the previous study and showed that the all-epiphyseal technique most effectively restored normal knee kinematics, while the iliotibial band technique led to joint over constraint under loading conditions mimicking the pivot shift test [37]. Another performed by McCarthy et al. compared the AE reconstruction and the over-the-top (OT) reconstruction in their ability to restore stability, knee kinematics, and regional contact stresses in cadaveric knees. Both techniques provided rotational and anterior stability and decreased posterior joint contact stresses compared to the knees with ruptured ACLs. However, they did not restore normal kinematics relative to the intact ACL intact knee and had some differences in contact stress patterns compared to the intact ACLs. Despite the similarity in results, the authors advocated for AE reconstruction, given clinical advantages over the OT technique [38].

Clinical outcomes of reconstructive techniques

Physeal sparing with iliotibial band reconstruction

Since the functional outcomes of the modified Macintosh technique were initially described by Kocher, Micheli et al., little has been published on clinical outcomes. However, a recent retrospective review evaluated 21 patients who were treated with the technique with a minimum follow-up of 3 years. Overall, excellent results were obtained with outcome scores being extremely high (IKDC = 97 and Lysholm = 95). The failure rate (14 %) and reoperation rate (27 %), however, were higher than those previously reported in the initial technique description. In this series, no angular or leg length discrepancies were identified [39•].

Physeal sparing with all-epiphyseal reconstructions

The first description of an all-epiphyseal ACL reconstruction was by Anderson et al. in 2004. Since that time, multiple variations of this technique have been described and multiple small case series have reported outcomes [40–45]. Over the last 3 years, several level IV retrospective case series have been added to the literature. The largest series to date was performed by Cruz et al. evaluating 103 skeletally immature patients. At a mean follow-up of nearly 2 years, the overall complication rate was 16.5 %, including 11 re-ruptures (10.7 %), one case (<1.0 %) of clinical leg-length discrepancy of <1 cm, and two cases (1.9 %) of arthrofibrosis requiring manipulation under anesthesia. However, functional outcome measures were not reported in this series [40]. A separate retrospective study utilizing post-operative MRIs to assess physeal compromise after an all-epiphyseal ACL reconstruction was performed in 15 patients. The results showed that the tibial physis was disturbed in 67 % of patients, but this involved only 2.1 % of the cross-sectional area of the physis. The femoral physis on the other hand was only disturbed in one case and compromised only 1.5 % of the cross-sectional area. In this series, no cases of growth arrest, leg length discrepency, or angular deformity were identified [41].

Transphyseal reconstruction

Over the last 3 years, multiple retrospective studies investigating transphyseal techniques have been performed, several of which report longer term outcomes. Calvo et al. have the longest mean follow-up of any series in the literature, with a cohort of 27 skeletally immature patients, and a minimum follow-up of 10 years. With their transphyseal technique using vertically oriented tunnels and semitendinosus-gracilis autograft, subjective outcomes were maintained over time with a mean Lysholm score of 92 and an IKDC score of 94. There were a total of four (14.8 %) graft ruptures. Of these four, three (11.1 %) were traumatic graft ruptures related to contact sports and one (3.7 %) was identified arthroscopically following progressive instability [46•]. Seven other retrospective case series were identified over the last few years with cohort volumes ranging from 15 to 30. The mean Lysholm and IKDC scores for all of these series were >90, and there was only a single case of a growth abnormality which consisted of a valgus deformity [47–53].

Comparative studies

To date, there are no randomized controlled studies or even prospective comparative studies comparing outcomes or complications between the various surgical techniques. However, Pierce et al. performed a systematic review which included raw data from 27 reports to compare transphyseal and phyeal-sparing techniques. The authors found that those who underwent physeal-sparing techniques were significantly younger (12 vs 13.5) than those who underwent transphyseal reconstruction. The incidence of limb length and angular deformities was not different between the two cohorts. The rerupture rate in the transphyseal cohort was 6.2 % after 6-year follow-up, and 3.1 % in physeal sparing, though this was not a significant difference [54].

Complications

Since Kocher et al. published a survey study of the Herodicus Society and the ACL Study Group in 2002, much attention has focused on growth disturbances after ACL reconstructions in the skeletally immature [55]. Over the last 3 years, three small case series have been published reporting growth abnormalities after an ACL reconstruction in a skeletally immature patient. Shifflett presented four cases with growth arrest in patients undergoing a transphyseal reconstructions, two of whom developed recurvatum deformities and two of whom grew into genu valgum. Ultimately, three of these patients required surgery to correct their deformity [56]. Zimmerman reported a single case of tibial overgrowth of 3 cm following a transphyseal reconstruction, which required an epiphysiodesis, and Koch et al. also reported an additional two cases of overgrowth after physeal sparing, all epiphyseal reconstruction [57, 58]. Currently, the most comprehensive review in the literature assessing growth abnormalities after an ACL reconstruction was performed by Collins et al. In this review, 39 patients were identified from 21 different studies. The most common growth disturbance was a leg length discrepancy (29 cases) with overgrowth being observed more when an all-epiphyseal technique was employed compared to relative shortening of the operative limb, which was observed more frequently when the transphyseal technique was performed. Angular deformities were not uncommon and accounted for 41 % of the growth abnormalities [59•].

Graft considerations

When utilizing either an all-epiphyseal or transphyseal ACL reconstruction technique, there are three primary graft options including hamstring tendon autograft (either semitendinosus, triple—or quadruple-looped), quadriceps tendon autograft, and soft-tissue allograft. Historically, hamstring autograft and allograft have been the preferred grafts, but recent investigations have focused on the quadriceps tendon. A recent ultrasound study on children revealed that the quadriceps tendon length averaged 4 cm at age 4 years and lengthened to 8 cm by age 16 [60]. The thickness averaged 2.5 mm at 4 years and increased to 4 mm at 16 years. The authors concluded that the quadriceps tendon is of sufficient length and thickness to be used as an autograft for pediatric patients. Over the last 3 years, only a single case series has been published involving use of the quadriceps tendon in children. This prospective study of 15 patients with a mean age of 12.8- and 4-year follow-up demonstrated excellent results with no graft ruptures, a mean Lysholm score of 94, but one growth disturbance was identified in a patient that developed genu valgum [52].

Few comparative studies exist in the literature evaluating different graft options in this skeletally immature population. In particular, there is no strong evidence that autografts yield superior clinical outcomes compared to allografts or vice versa; additionally, the existing evidence mostly pertains to the adults population [61]. A recent retrospective study compared transphyseal reconstructions performed with allograft versus autograft [53]. The failure rates between groups, while not statistically significant, averaged 38 % in the allograft group compared to 9 % in the autograft group. A separate study using the Kaiser database evaluated revision rates in 534 skeletally immature patients undergoing an ACL reconstruction [62]. They found similar findings to the previous study where the soft tissue allografts had a higher failure rate of 13.2 % compared to the hamstring autografts (7.5 %), but this also did not reach statistical significance. A recent systematic review focusing on allografts by Park et al. analyzed 21 publications involving a total of 1453 patients, to determine the effect of allografts treated with different processing techniques on clinical outcomes. There were 415 patients with irradiated allografts and 1038 with non-irradiated allografts with an average age of 32 years. The study reported that knees with non-irradiated allografts had higher mean Lysholm scores and greater knee stability than those with irradiated allografts [63]. Given this existing literature and data from the MOON Consortium revealing 60 % increased odds of graft failure with every 10-year decrease in patient age, most of the pediatric sports community has moved away from consideration of allograft for ACL reconstruction [64].

Post-operative considerations

An important consideration in the surgical treatment of ACL injuries in pediatric patients is post-operative pain control modalities. Femoral nerve blocks are one option that may improve VAS scores and decrease opioid use post-operatively. These blocks are not without risk and include motor weakness and transient femoral neuropathy. A recent study evaluated knee strength and function 6 months after ACL reconstruction in pediatric and adolescent patients and noted that those patients that received a femoral nerve block had weaker quadriceps and hamstring muscles in several testing categories. Although no differences in functional testing were identified between groups, those who did not receive a block were more likely to meet criteria for return to sport at 6 months [65]. Post-operative rehabilitation also plays an important role in safely returning young athletes back to sport. While rehabilitation progression, performance measures, and expected outcomes are defined in the adult population, these are lacking in the skeletally immature population. Boyle et al. attempted to elucidate factors, which may predispose adolescent patients to graft failure. The Functional Movement Screen and a dynamic balance assessment were performed on 39 adolescent patients, 17 skeletally immature, and 22 skeletally mature, who underwent an anatomic, transphyseal hamstring autograft ACL reconstruction. These groups were compared to an adult control cohort of 16 primary ACL patients. The results of the study revealed that adolescent patients did not consistently recover adequate functional movement patterns by 9 months post-operatively to permit a safe return to sport and suggest a need for maturity-specific rehabilitation programs [66]. Another study by Greenberg et al. suggested a need for prolonged post-operative rehabilitation in the skeletally immature population after ACL reconstruction. They studied 16 patients with a mean age of 12.28 years who underwent all-epiphyseal ACL reconstruction and reported significant strength and functional deficits after 1 year [67]. This is consistent with the findings that a large percentage of patients were unable to return to sport at their prior level [43]. In deciding when patients are able to return to sport, some studies have suggested that more symmetric quadriceps femoris strength should first be achieved, since QF strength asymmetry alters landing patterns [68].

Risk factors and prevention

An important aspect of both primary and secondary injury prevention is identification of patients who are at greater risk for ACL rupture. Risk factors for ACL injury can be modifiable or non-modifiable. In the past 3 years, a number of studies have investigated non-modifiable risk factors for ACL rupture in skeletally immature patients. A study by Samora et al. in 2015 found a correlation between a decreased angle of inclination of the intercondylar roof (RIA) and patients with ACL tears. This was in contrast to patients with tibial spine fractures who had increased RIA [69]. In 2015, O'Malley et al. performed a retrospective case control study in patients with open physes, demonstrating a moderate association between increased posterior tibial slope and ACL injury in the pediatric population [70•]. This is consistent with the findings from Dare et al., who proposed that a cutoff of greater than 4 degrees for the posterior slope of the lateral compartment is 76 % sensitive and 75 % specific for predicting ACL injury in skeletally immature patients [71]. Another group conducted a retrospective review of 39 MRI studies and found the notch width index to be significantly smaller in the ACL injury group compared to an age-matched control group [72]. Patella alta has also been implicated as a non-modifiable risk factor for ACL injuries in patients with open physes. This study demonstrated an association between ACL tear and increased patellar tendon length with a greater Insall-Salvati ratio [73].

Recent reports have shown that decreased neuromuscular control and high-risk biomechanics of movement are predictors of injury and re-injury [74–76]. Improved understanding of these biomechanical, anatomic, and kinematic risk factors of ACL injuries has led to the development of ACL injury prevention programs. These programs have components of neuromuscular, proprioceptive, and plyometric training targeted at minimizing impairments that may lead to injury and re-injury and have been shown to be effective in decreasing the rate of ACL injuries in high school, college, and professional players [77–83]. Over the last 3 years, several studies have investigated the utility of these prevention programs in young athletes. Walden et al. performed a randomized controlled trial using a neuromuscular warm-up program targeting balance, proper knee alignment, and core stability in female Swedish football players and found that the program led to a 64 % reduction in ACL injuries [84]. A follow-up study on this cohort revealed that higher compliance with the program led to greater injury reduction, but there was an overall deterioration in compliance that occurred during the course of the season [85]. A recent study also evaluated the landing mechanics in young adolescent athletes with a mean age of 13 years. The results showed that female athletes demonstrate less desirable landing biomechanics than their male peers. The authors go on to suggest that the first year in high school, when early adolescent females are first exposed to high school sports, may be an ideal time to assess movement quality during functional tasks and intervene with injury prevention programs if necessary [86].

Conclusion

ACL ruptures are increasingly being diagnosed in the skeletally immature population and have been associated with chondral and meniscal pathologies. In an attempt to lessen future instability events, surgeons are becoming more aggressive about early reconstructive surgery, instead of bracing and modifying the patient's activity until they reach skeletal maturity. Increasing knowledge of ACL and epiphyseal dimensions may be helpful in planning graft options, tunnel placement, and surgical technique. While multiple reconstruction techniques exist for this patient population, each with their distinct advantages and disadvantages, reported clinical outcomes are uniformly favorable. Existing biomechanical evaluations examining the various surgical treatments all report improved post-operative stability and kinematics relative to ACL-deficient knees, but these studies have not clearly identified a superior surgical technique. Physicians need to be aware that complications still occur with graft rupture being the most common. Recent literature has found greater failure rates in soft tissue allografts compared to autografts. Additionally, new cases of growth disturbance in this population including leg length discrepancies and angular deformities, although rare, are still being identified. Therefore, patients with open growth plates undergoing an ACL reconstruction need to be followed clinically until skeletal maturity. Successful ACL injury prevention programs have been developed, but as more modifiable and non-modifiable risk factors for ACL rupture are identified, more targeted prevention strategies should be developed.

Compliance with ethical standards

Conflict of interest Michael M. Murphy and Mark Wu declare that they have no conflicts of interest.

Andrew Pennock is a committee member of AOSSM and POSNA. He is on the editorial board for Arthroscopy and is a reviewer for AJSM and JPO.

Human and animal rights and informed consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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