Pediatric Anterior Cruciate Ligament Reconstruction

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KEYWORDS

• Anterior cruciate ligament • ACL Reconstruction • Pediatric • Adolescent • Knee
• Skeletally immature

KEY POINTS

- Anterior cruciate ligament injuries are the most common cause of traumatic knee effusion in adolescents and are occurring with an increasing incidence.
- Assessment of skeletal age and growth remaining is critical to treating skeletally immature patients with anterior cruciate ligament tears.
- Nonoperative treatment of anterior cruciate ligament tears, even in the youngest patient, is associated with secondary chondral and meniscal injury and is not appropriate for the majority of patients.
- Physeal-sparing, partial transphyseal, and transphyseal anterior cruciate ligament reconstructions allow for stabilization of the knee while respecting the various amounts of growth remaining of children and adolescents.

INTRODUCTION

Anterior cruciate ligament (ACL) injuries in children and adolescents have increased in prevalence in the last 2 decades. According to recent estimates, ACL injuries in this population occur with an incidence of 14 per 100,000 exposures.[1] ACL reconstructions in patients younger than 15 years increased by 425% from 1994 to 2006.[2] An increasing number of young athletes (38 million participating in organized sports in 2009 to 2010),[1] year-round sports participation, and earlier single sport specialization have all been proposed as theories for this trend.[3,4]

Historically, skeletally immature athletes with ACL tears were managed with activity modification and bracing, largely owing to concern for physeal damage from standard reconstruction techniques. However, there are significant risks of secondary chondral and meniscal damage associated with delayed reconstruction.[5,6] As the evidence in support of early reconstruction has accumulated, practice patterns have changed in favor of operative intervention. An understanding of physeal anatomy and reconstructive options is vital when planning surgery for children and adolescents with ACL injuries. The purpose of this article is to review the anatomy of the ACL and pediatric knee, imaging and diagnosis of ACL injuries, and unique operative techniques for treatment of these injuries in skeletally immature children and adolescents.

ANATOMY AND FUNCTION OF THE ANTERIOR CRUCIATE LIGAMENT

The ACL is the primary restraint of anterior translation and rotation of the tibia on the femur and is maximally loaded at 30° of flexion.[7] The ACL originates on the lateral femoral condyle and inserts on the medial intercondylar spine of the tibia. As the knee passes through a range of motion, the ligament changes in orientation, from more vertical in extension and horizontal in flexion.[8] The lateral bifurcate ridge separates the anteromedial bundle and posterolateral bundles of the ACL within the femoral footprint, but the bundles are named

Disclosure Statement: The authors have nothing to disclose.
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Orthop Clin N Am 51 (2020) 55–63
https://doi.org/10.1016/j.ocl.2019.08.009
0030-5898/20/

based on their insertion on the tibia.[9] The ACL is not an isometric structure. As the bundles change in orientation through a range of motion, the anteromedial bundle is tight at high-flexion angles and the posterolateral bundle is tight at low-flexion angles.[10]

The origin and insertion of the ACL are in close proximity to the distal femoral and proximal tibial physes. Authors have described the relationship of the origin and insertions of the ACL to the distal femoral and proximal tibial physis.[11–13] An understanding of physeal anatomy is vital when planning surgery for children and adolescents with ACL injuries and open physes.

CLINICAL EVALUATION OF AN ANTERIOR CRUCIATE LIGAMENT TEAR

A high index of suspicion for an intra-articular injury must be had for all patients with a traumatic knee injury and an effusion. ACL tears are the most common cause of an acute traumatic knee hemarthrosis.[14] Patients with a knee effusion who report a pop in the knee after an acute knee injury have a 70% chance of an ACL tear.[14] ACL tears and patellar dislocations or subluxations are easily confused. An effusion, lateral knee pain and tenderness, and injury sustained from a jump landing or while pivoting are common findings in ACL injury patients, but also patients with a patellar subluxation or dislocation. We frequently diagnose patients with an ACL tear after a reported history or even treatment for presumed patellofemoral instability. Careful examination is necessary to avoid this diagnostic pitfall.

The physical examination of the knee is critical to diagnosis of ACL injuries, as well as concomitant injuries such as collateral ligament or meniscal tears. Dynamic examinations, such as the Lachman and pivot shift, should be compared with the uninjured knee. In these young patients, examination of the uninjured knee is essential to allow assessment of physiologic laxity, which is often present in this age group. Additionally, an examination of the well leg allows the patient to experience the examination maneuvers performed on the uninjured, and nonpainful, limb helping to relax the patient in this often-anxious age group. Initial imaging should include AP, lateral, notch, and sunrise views of the injured knee to assess for physeal status, fractures, and other underlying problems such as osteochondritis dissecans. In skeletally immature patients, standing long-leg alignment radiographs are important to assess for limb length inequalities or angular deformities. A posteroanterior left hand radiograph is also necessary in skeletally immature patients to determine skeletal age and is the authors' favored method for calculating skeletal age and growth remaining. MRI is the gold standard imaging modality for the diagnosis of ligament, meniscus, and chondral injuries of the knee. Recognition of associated injuries is critical to surgical planning and optimal treatment of traumatic knee injuries.

ASSESSING SKELETAL MATURITY

The physes about the knee produce substantial growth of the lower extremity with the distal femoral physis contributing 70% of femoral growth (9 mm/y) and the proximal tibial physis contributing 60% of tibial growth (6 mm/y). Assessments of skeletal maturity in the literature have historically been done by chronologic age, presence of an open physis on plain radiography, Tanner staging of secondary sexual characteristics, bone age, and combinations of these methods. Chronologic age and the presence of an open physis on radiographs are notoriously inaccurate. Tanner staging is based on dividing secondary sexual characteristics into 1 of 5 groups.[15] These stages parallel the adolescent growth spurt and subsequent closure of the physes. Unfortunately, they do not seem to be accurate; a study of experienced physicians performing these assessments has shown them not to be reliable or reproducible.[16,17] Additionally, Tanner staging has not been documented to predict the growth remaining at the distal femoral and proximal tibial physes.

Bone age uses a posterior-anterior radiograph of the left hand, which is then compared with standard examples in the Greulich-Pyle atlas.[18] Although perhaps one of the more objective methods available to us, there is a great deal of overlap and indetermination for any given radiograph. A shorthand version is now available but still relies on the standards from the Gruelich-Pyle dataset and assessment.[19]

In an attempt to determine the age at which it is feasible to perform a transphyseal ACL reconstruction, multiple authors have categorized patients into treatment groups based on Tanner stage and predictions of growth remaining. One such algorithm groups patients as prepubescent (Tanner stage 1–2, bone age $<$12 years in males and $<$11 years in females), pubescent (Tanner stage 3–4, bone age 13–16 years in males and 12–14 years in females), or older adolescents (Tanner stage 5, bone age $>$16 years in males and $>$14 years in females).[20] Based on bone age, treatment recommendations are that prepubescent patients are treated with physeal-sparing reconstructions, adolescent patients with transphyseal reconstruction with soft tissue grafts, and older adolescents with a conventional ACL reconstruction with either soft tissue or bone–patellar tendon–bone grafts.[20]

Guzzanti and associates[21] introduced the concept of growth remaining and proposed categorizing children into 3 groups based on their risk for growth disturbance (high, intermediate, and low). High risk were preadolescents who had a lower extremity growth potential of more than 7 cm and included Tanner stage 1 children with a bone age in females of less than 11 years and in males of less than 12 years. The intermediate group had lower extremity growth potential of 5 to 7 cm and included Tanner stages 2 and 3 and bone age in females 11 to 13 years and in males 12 to 15 years. Last, the low-risk patients had less than 5 cm of growth remaining and included Tanner stages 4 and 5 and bone age in females greater than 14 years and males greater than 16 years. Using this algorithm, partial transphyseal reconstructions in 10 patients deemed at intermediate risk and followed to skeletal maturity (24–108 months) resulted in no significant limb length discrepancies.[21]

Kelly and Dimeglio[22] have published tables that illustrate the growth remaining of the distal femur and proximal tibia based on a patient's bone age (**Fig. 1**). These tables effectively group patients in to 3 groups based on combined growth remaining around the knee: less than 1 cm, 1 to 5 cm, and more than 5 cm. The authors use Dimeglio's principal of growth remaining to guide their ACL reconstruction technique, and this is described further in the Preferred Approach section.

The goal of ACL reconstruction is to restore knee stability while protecting growth. The risk of physeal damage with limb length discrepancy and angular deformity has to be weighed against the risk of leaving the knee unstable in these highly active youth who have a limited propensity to self-restrict from risky activities. Physicians taking care of ACL tears in skeletally immature patients should be proficient in assessing growth remaining, understanding and minimizing the risks of traditional transphyseal ACL reconstruction based on basic science and clinical evidence, choosing between a transphyseal technique or other alternatives such as physeal-sparing reconstructions, and monitoring patients after surgery for potential growth disturbances.

PHYSEAL ANATOMY AND ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

Numerous animal studies have helped to define the anatomy of the physis and its response to trauma. As early as 1959, Campbell and coworkers[23] described growth retardation that resulted from a single large hole drilled through the open physes of dogs and complete growth arrest from cortical bone placed across a transphyseal tunnel. Tunnel size can also impact the physis. Transphyseal tunnels violating 7% to 9% of the cross-sectional area of the physis in rabbits resulted in a permanent growth disturbance, whereas smaller defects of 3% to 4% did not.[24,25] Together, these animal studies suggest

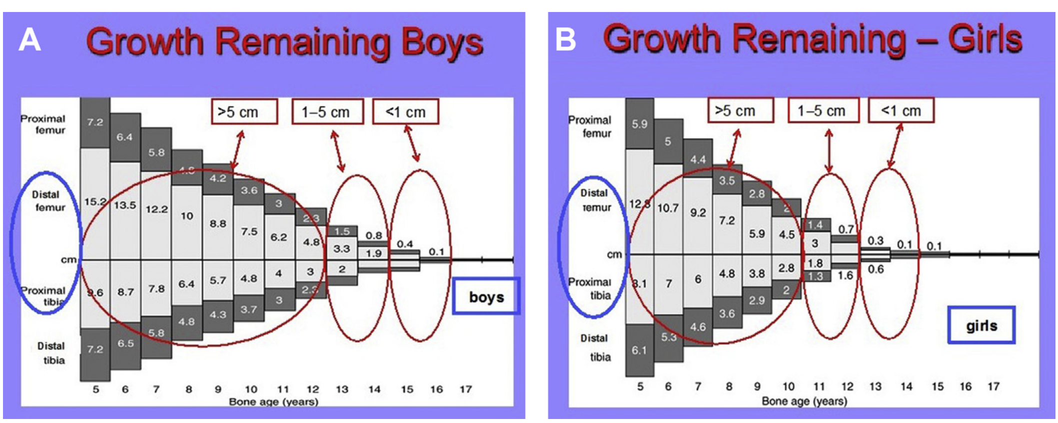

Fig. 1. Growth remaining of the distal femur and proximal tibia based on a patient's bone age: (*A*) for boys and (*B*) for girls. (*From* Perkins CA, Willimon SC, Busch MT. Transphyseal ACL Reconstruction in Skeletally Immature Patients. In: Parikh SN, editor. The Pediatric Anterior Cruciate Ligament: Evaluation and Management Strategies, 1st edition. Cham: Springer International Publishing AG; 2018; with permission.)

that soft tissue grafts placed in transphyseal tunnels across less than 5% of the cross-sectional area of the physis prevent formation of physeal bars; however, tethering may explain occasional angular deformities about the knee.[26]

Radiograph-based computer models have tried to evaluate tunnel characteristics across open physes. Kercher and colleagues[27] obtained 3-dimensional models of the physes from patients with an ACL tear on MRI. By mapping 8-mm tunnels, these investigators calculated a violation of 2.4% of the distal femoral and 2.5% of the proximal tibial physes.[27] Using a similar 3-dimensional modeling technique, Shea and associates[28] found that increasing the tibial tunnel drill angle from 45° to 70° from the horizontal decreases volume removed from 4.1% to 3.1%. However, the benefits of damaging less physis by using vertical tunnels have to be weighed against the detrimental biomechanical effects of these less anatomic and physiologic reconstructions.

OPERATIVE TREATMENT

There have been numerous studies that compare outcomes of operative and nonoperative treatment of ACL injuries in skeletally immature patients.[6,29–35] A systematic review and meta-analysis published in 2013 showed dramatic benefit to early operative management.[36] Symptoms of instability were reduced from 75% to 14%, the incidence of medial meniscal tears was reduced from 35% to 4%, and the ability to return to sports increased from 0% to 86% with timely reconstruction. As a result, operative treatment, rather than nonoperative treatment, is considered the standard of care in even the youngest athletes with an ACL injury. Physeal-sparing (extraphyseal and all-epiphyseal), partial transphyseal, and transphyseal reconstructions are all acceptable techniques based on the patient's skeletal age, physician preference, and shared decision making.

PHYSEAL-SPARING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

Physeal-sparing ACL reconstructions offer the benefit of avoiding bone tunnels that cross the physis, and are therefore appropriate for the youngest children with the greatest growth remaining. The first descriptions of a physeal-sparing technique were by David MacIntosh and associates[37] in 1976, who developed an extra-articular reconstruction using an iliotibial band autograft for chronic ACL deficiency in adults. The graft was harvested proximally, left intact at Gerdy's tubercle, passed deep to the fibular collateral ligament, and sutured back to itself. Micheli and colleagues[38] later described a modification of this technique to include a combined extra-articular and intra-articular reconstruction as a physeal-sparing reconstruction in skeletally immature children and adolescents. The iliotibial band is passed superficial to the fibular collateral ligament to an over-the top position on the femur, through the intercondylar notch, beneath the intermeniscal ligament, and then sutured to the periosteum of the proximal tibia and lateral femur.[38] Although cited by some as a nonanatomic reconstruction, biomechanical testing has shown restoration of native constraint[39] and clinical outcomes cite low revision rates with this technique.[40–42]

ALL-EPIPHYSEAL ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

All-epiphyseal ACL reconstructions offer similar benefits to the physeal-sparing iliotibial band reconstruction, but with the advantage of restoring the anatomic footprint of the ACL. Biomechanical testing of this technique demonstrates restoration of normal knee kinematics, while also decreasing the posterior joint contact stress as compared with the ACL-deficient knee.[39,43] Several all-epiphyseal ACL reconstruction techniques have been described, including the Anderson,[44] Ganley-Lawrence,[45] and Cordasco-Green,[46] each with unique tunnel drilling and fixation techniques. The Anderson technique[44] was described in 2004 and features outside-in epiphyseal bone tunnels, a quadrupled hamstring autograft, and suspensory femoral fixation and either a metaphyseal post or epiphyseal suspensory device for tibial fixation. The Ganley-Lawrence technique[45] was described in 2010, uses a quadrupled hamstring autograft, and features retrograde inserted interference screws for fixation in both the femur and tibia, thereby avoiding any tunnels or fixation across the physis. Another all-epiphyseal technique, the Cordasco-Green modification,[46] uses bone sockets (rather than tunnels) and cortical suspensory buttons for fixation. This fixation strategy is proposed to provide greater contact of the graft to the surrounding bone by avoiding interference fixation. All-epiphyseal techniques are not without risk to the physis. Lawrence and coworkers[47] reported a premature lateral distal femoral physeal closure associated with an all-epiphyseal femoral tunnel, potentially secondary to thermal injury from tunnel drilling. In contrast, other authors have described overgrowth resulting in leg-length discrepancy requiring subsequent guided growth following an all-epiphyseal tunnel, hypothesizing that the increased vascularity after periosteal disruption stimulated the increased growth of the surgical limb.[48,49] Cruz and colleagues[50] reviewed a single-center series of 103 patients treated with all-epiphyseal ACL reconstructions and identified an overall complication rate of 16.5%, including 11 graft ruptures, 1 leg-length discrepancy of greater than 1 cm, 2 cases of arthrofibrosis requiring manipulation under anesthesia, and 3 patients with subsequent ipsilateral meniscus tears. These complications raise concerns that all-epiphyseal ACL reconstructions are not without risk in patients with growth remaining.

All-epiphyseal reconstructions are growing in popularity for very young patients, but require long-term outcome studies with close follow-up for this relatively rare group of very young patients with ACL tears.

PARTIAL TRANSPHYSEAL ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

Partial transphyseal ACL reconstructions were described as early as 1986 with over-the-top physeal-sparing femoral graft fixation and a transphyseal tibial tunnel.[51] Several other authors have described a similar over-the-top femoral graft position and a transphyseal tibial tunnel.[52,53] More recently, Milewski and Nissen[54] have described an all-epiphyseal femoral tunnel and a transphyseal tibial tunnel to allow for a more anatomic femoral tunnel position. For patients with 3 or more years of growth remaining, a partial transphyseal reconstruction offers the ability to avoid injury of the femoral physis while drilling a tibial tunnel, which is vertical and small with limited impact on the tibial physis. There are very limited outcome data for partial transphyseal ACL reconstructions. Chambers and colleagues[55] recently reported on 24 patients with a mean age of 12.3 years who underwent partial transphyseal ACL reconstruction with a hamstring autograft. The majority of patients had 2 to 5 years of growth remaining, which they defined as females with a chronologic age of 9 to 12 years and males with a chronologic age of 11 to 14 years. Mean graft size was 7.8 mm (range, 7–9 mm). Five patients (21%) experienced a growth disturbance, with 3 patients having a greater than 1 cm limb length discrepancy and 3 patients developing genu valgum. Most notable, was that of the 3 patients in the cohort with more than 5 years of growth remaining, 2 (67%) had a growth disturbance. There were 2 graft failures (8%) at a mean of 31 months of follow-up. Clearly, the youngest children with ACL tears may not be appropriate for this partial transphyseal technique. Future studies using bone age to predict growth remaining with functional outcomes will be necessary to determine the particular age group that is best treated with a partial transphyseal technique.

TRANSPHYSEAL ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

The vast majority of ACL tears in skeletally immature athletes occur in adolescents with limited growth remaining (<1 year). This allows for traditional transphyseal reconstructions with little risk for growth disturbance. With careful patient selection and attention to technical details, a transphyseal ACL reconstruction is a sound and viable treatment for most skeletally immature children.

A survey of the Herodicus Society and ACL study group was published by Kocher and colleagues[56] in 2002 and aimed to describe cases of growth disturbances resulting from ACL reconstruction in skeletally immature children. Among 140 surgeons, there were 15 growth disturbances reported, with 12 of these occurring after transphyseal reconstructions. Of these, 3 had hardware crossing the distal femoral physes and 4 had patellar tendon bone plugs crossing a physis, resulting in premature physeal closure and angular deformity. Two patients developed limb length inequalities, one associated with a 12-mm femoral tunnel and the other with a patellar tendon bone plug crossing the physis. The final 3 patients developed recurvatum associated with staples across the tibial tubercle and multiple sutures into the periosteum of the tibia. These technical flaws highlight the importance of a physeal respecting transphyseal reconstruction.

Shiflett and coworkers[26] published a report on 4 skeletally immature patients (ages at surgery 13.5–14.8 years) with growth arrest after transphyseal ACL reconstruction with a hamstring autograft. Two patients developed tibial recurvatum with closure of the tibial apophysis and 2 patients developed genu valgum. The authors postulated that the recurvatum occurred as a result of tenoepiphysiodesis, whereby excessive tensioning of the graft across the physis at the time of a rapid growth spurt led to tibial apophysis arrest. The etiology of the distal femoral arrests resulting in genu valgum was postulated to be the oblique trajectory of the femoral tunnel created through an anteromedial portal. Despite the use of soft tissue grafts with theoretically limited injury to the physes, this report reinforces that problems can occur, transphyseal ACL reconstruction in immature youths is not yet risk free, and these patients must be followed closely to skeletal maturity. However, the vast majority of studies of transphyseal reconstruction describe favorable outcomes with no significant length or angular deformities.[33,57–64]

AUTHORS' PREFERRED APPROACH

By using Dimeglio's growth remaining data[22] (see Fig. 1), the authors have divided children undergoing ACL reconstruction into 3 treatment groups that arguably have clinical implications (Table 1). Patients with less than 1 cm of growth remaining at the knee have virtually no risk of developing a meaningful growth disturbance. These are typically males with a bone age of 15 or 16 years and females with a bone age of 13 or 14 years. In this group of patients, we feel a transphyseal reconstruction is safe. Families can be counseled that complete or partial growth arrests with minimal growth remaining have not been demonstrated to cause significant deformity. As a result, conventional ACL reconstruction techniques and graft options can be considered with minimal to no modifications. Specifically, grafts that include bone blocks, such as patellar tendon or quadriceps grafts, can be used. These patients are followed clinically for at least 12 months and discharged once radiographs show that their physes surrounding the knee have closed. Alignment is followed clinically and long leg radiographs for limb alignment are not routinely obtained.

For those patients with 1 to 5 cm of growth remaining, who have a risk of developing an appreciable growth disturbance, there are several considerations that guide treatment. These are typically males with a bone age of 13 or 14 years and females with a bone age of 11 or 12 years. For them, a thoughtfully performed physeal-respecting transphyseal reconstruction is a viable option, and is our usual recommendation. Preoperatively, a left hand bone age and long leg alignment radiographs are obtained. Occasionally, we identify an existing coronal plane deformity, typically genu valgum, which may have contributed to the original ACL injury and be a risk factor for subsequent graft injury. Correction with hemiepiphyseal tethering and guided growth can be considered.

A soft tissue autograft is selected for this age group, with the most common graft being a quadriceps tendon in our practice. Tunnels are sized according to the diameter of the graft and positioned centrally in the physis. There is mixed literature regarding optimal graft size in adolescents, but if patients are approaching adult body habitus, we strive for a graft size of 8 to 9 mm. Graft fixation is performed on the femur using cortical suspensory fixation (through a femoral tunnel drilled using a tibial independent drilling technique) and a biocomposite interference screw or post placed distal to the physis on the tibia. Fixation placement is verified with fluoroscopy. Distal fixation can be supplemented with a staple, post and washer, or anchor as deemed necessary. Careful placement of the tibial tunnel and fixation is needed to avoid additional risk of damage to the tibial tubercle and perichondral tissue.

Patients and families are advised of the risks of growth disturbance associated with this technique, but are reassured that reasonable precautions will be taken to minimize these risks and the patients will be monitored afterward to identify any growth-related abnormality. If necessary, treatment can be undertaken in a timely manner to diminish the effect of the growth disturbance and minimize the need for future interventions. Postoperatively, the examination of limb lengths and alignments is documented at each visit. If we have a clinical concern for length or angular deformities, then lower extremity alignment radiographs are obtained and may be compared with preoperative limb alignment radiographs.

For patients with more than 5 cm of growth remaining, the consequences of a growth disturbance are more significant given the amount of growth remaining. Therefore, we recommend a physeal-sparing reconstruction. This patient group typically includes males with a bone age

Table 1
Growth-based surgical strategy

Growth (cm)	Girls	Boys	Prescription
<1	≥13	≥15	Standard procedure
1–5	11–12	13–14	Transphyseal
>5	≤10	≤12	Physeal sparing

From Perkins CA, Willimon SC, Busch MT. Transphyseal ACL Reconstruction in Skeletally Immature Patients. In: Parikh SN, editor. The Pediatric Anterior Cruciate Ligament: Evaluation and Management Strategies, 1st edition. Cham: Springer International Publishing AG; 2018; with permission.

of 12 years or less and females with a bone age of 10 years or less. In our hands, this is most commonly the iliotibial band reconstruction modified by Micheli[40] and published by Micheli, Kocher, and others.[40–42] This technique has produced good results in our practice with low failure rates and no apparent growth disturbances in our youngest patients.

REHABILITATION

In addition to careful surgical technique, a structured rehabilitation program with experienced physical therapists is important to ensure optimal outcomes after ACL reconstruction. Standard rehabilitation protocols include progressive strengthening, proprioception, and endurance. A functional testing regimen is completed at 6 months postsurgery to guide us in advancing patients to the last 3 months of a return to sport progression. Return to unrestricted cutting and pivoting sports is routinely no sooner than 9 months. This schedule is supported by reduced reinjury rates for each month that return to sports is delayed until 9 months after surgery.[65] Ultimately, a return to sport progression is guided by a combination of surgeon discretion and functional testing results. Full clearance is not provided until functional testing demonstrates safe landing mechanics and appropriate neuromuscular control, and may require 12 months or longer to achieve. Establishing clear patient and family expectations regarding restrictions and estimated return to play is critical to successful outcomes and maximizing compliance and should be a routine part of the preoperative discussion.

SUMMARY

The increasing incidence of ACL injuries in skeletally immature children demands careful attention by orthopaedic surgeons. In addition to chronologic age, assessment of skeletal age is essential to select the appropriate ACL reconstruction technique. Males with a bone age of 15 years or older and females of 13 years and older are ideal candidates for a transphyseal ACL reconstruction. Families can be reassured that there is minimal risk of growth disturbance in this age group, and few additional considerations are required for an optimal outcome.

Based on the current evidence, transphyseal ACL reconstructions with soft tissue grafts are relatively safe and effective for skeletally immature adolescents whose skeletal age is 13 or 14 years in males and 11 or 12 years in females. In this population, the risk for limb length discrepancy and angular deformity is low, but requires assessment, planning, informed consent, documentation, a physeal-respecting surgical technique, and appropriate follow-up. Children with substantial growth remaining (skeletal age boys 12 years or less and girls 10 years or less) seem to be at risk for greater significant growth disturbance, so we generally recommend physeal-sparing techniques for these younger patients.

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