Pediatric ACL Injuries: Challenges and Solutions, from Prevention to Operative Reconstruction

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Pediatric anterior cruciate ligament (ACL) injuries have been the source of much debate in the literature. Tibial eminence avulsion fractures were thought to be more common than mid-substance ACL tears in skeletally immature patients. However, this has changed in recent years, with a growing number of ACL ruptures in this age group from increased participation in sports at a younger age, especially among females. Treatment of ACL ruptures in patients with open growth plates has been a challenge because physicians must weigh the risks of early surgical treatment, such as growth arrest and angular deformities from disruption of the growth plate, with the risks of delay in surgery, such as increased meniscal and chondral pathology from chronic instability. Multiple surgical techniques have been developed to respect or avoid the femoral and tibial physes. Recent data has highlighted the risks associated with delaying surgery and has renewed an interest in early reconstruction. ACL prevention programs have been developed and modified for pediatric patients that have been shown to decrease ACL injury risk. Incorporation of these programs by coaches should help to reduce the incidence of ACL ruptures in high-risk patients such as female soccer players.

Introduction

Casual and elite level athletes involved in team sports can benefit from the enjoyment, camaraderie, gains in endurance, strength and flexibility, as well as the development of fitness habits from involvement in team sports. A significant negative to sports participation is the increased risk of injuries. The incidence of anterior cruciate ligament (ACL) tears ranges from 1%-3%[1-5] and may be higher for athletes that compete in year-round sports. The incidence in children has increased in the past decade due to increased training intensity, increased training time with year-round sports, increased competitiveness at early ages, and early exposure to high demand sports such as football, soccer, and skiing[6]. ACL ruptures were once thought to be rare in children. It was previously believed that patients with open physes are more likely to have a tibial spine avulsion fracture than an ACL rupture, but mid-substance ACL ruptures are now being recognized more commonly in patients with open physes[7].

ACL prevention programs, nonoperative treatment, and ACL reconstructions are all topics that have garnered a great deal of interest in medical literature as well as lay press articles. In this article, we discuss our approach to ACL injuries in the pediatric patient.

Epidemiology

It is estimated that there are about 2 million high school sports injuries per year. Costs are estimated to be approximately $1.8 billion per year[6]. Sports injuries such as ACL tears are more common in males, but that is likely related to the greater number of males in sports. The number of males with ACL tears is greater, but females have a higher rate of injury per exposure. Female athletes are 2 to 10 times more likely than males to sustain an ACL injury in landing and cutting sports[8]. Our team at the Sports Medicine and Performance Center analyzed 15 high schools in the Philadelphia area and looked at over 5,000 athletes and nearly 800,000 athlete-hours of exposure time in 6 gender matched sports. We found that females had greater risk and rate of injuries in soccer, basketball, track, cross country, and baseball/softball. The knee, tibia, and ankle were the most frequently injured body parts.

Participation in organized sports among females has increased 1000%, largely due to the incorporation of Title IX in 1972. The National Federation of State High School Associations (NFSHSA) reported that over 3.2 million female athletes participate in high school sports programs annually[9].

ACL Risk Factors and ACL Injury Prevention

There are four key imbalances that can place athletes at higher risk for ACL injuries. These include ligament dominance, quadriceps dominance, leg dominance, and trunk dominance[8,10-11]. Ligament dominance is the tendency to allow stress on ligaments before muscular activation when absorbing forces. This places high torque at the knee with increased force and valgus motion during landing. Quadriceps dominance is the activation of knee extensors preferentially over knee flexors during sports movements to stabilize the knee joint. This leads to imbalances in strength and coordination between the quadriceps and knee flexors. Quadriceps activation with the knee in relative extension has been shown to generate enough anterior translation force at the knee to tear the ACL and is thought to be

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one of the final common pathways leading ultimately to ACL tears[12]. Leg dominance is the imbalance between strength and coordination between an athlete's legs. This places both limbs at an increased risk of ACL injury. Trunk dominance is the tendency for an athlete to have excessive trunk motion in the frontal or coronal plane during landing, pivoting, or deceleration. This leads to increased ground reaction forces as well as a higher knee load[13]. Hip rotational angular velocity during jump landing is an additional risk factor.

ACL prevention programs are designed to teach at-risk athletes to avoid vulnerable positions, improve strength and flexibility, and improve proprioception[8]. Published studies have shown that neuromuscular training from ACL prevention programs have led to significantly decreased ACL injuries in athletes in landing and cutting sports[8, 10-11, 13-22]. The proper position for the knee during landing provides an optimal ability to absorb the force of impact. This involves a balanced position with both feet under control and the tibia in neutral rotation with the knee flexed. An ACL prevention program designed for pediatric athletes can be incorporated into their pre-practice warm up. Our prevention program is now web-based[23].

Steps can also be taken in order to prevent all types of sports injuries in children. These include recognition of health needs through screening, recognition of dangerous field conditions, use of proper protective equipment, age appropriate sports training, identification of characteristics of those more prone to injuries, moderating excessive overly intense and year-round sports, and ensuring that the chosen activity is enjoyable. The responsibility of ensuring these steps are taken falls not only on health care providers, but on coaches, parents, and teammates as well.

Operative Versus Non-Operative Management of Mid-substance ACL Disruption:

There has been a debate on how to approach the management of ACL disruption in skeletally immature patients. Many have advocated an initial non-operative approach that incorporates activity modification, bracing, and continued rehabilitation until the patient reaches skeletal maturity. The challenges to the delay to surgery approach include noncompliance, and the possibility of increased injury to the articular cartilage and meniscus. Multiple studies have shown that initial non-operative management has led to chronic instability and a high incidence of meniscal injuries[24-27]. A study by Graf et al. showed that bracing alone does not prevent meniscal tears in the absence of activity modification[26].

Some experts advocate for initial operative treatment of young patients with mid-substance ACL disruption[6]. However, there are significant risks to early reconstruction in patients with growth remaining. The main risk is the formation of physeal bars, which can lead to growth arrest and sagittal and/or coronal angular deformity. The distal femoral physis produces 70% of the femoral growth, averaging 1.2 cm per year. The proximal tibial physis is responsible for 60% of tibial growth at an average of 0.9 cm/yr[7]. In 2002, the Herodicus Society and the ACL Study Group reported fifteen cases of growth disturbance, including 8 cases of distal femoral valgus deformity with arrest of the lateral distal femoral physis, 3 cases of tibial recurvatum with arrest of the tibial tubercle apophysis, 2 cases of genu valgum without arrest, and 2 cases of leg length discrepancy[28].

Animal studies have demonstrated mixed results with growth disturbances from transphyseal drilling. Stadelmaier et al. found no evidence of growth arrest in all four dogs with a non-tensioned, soft-tissue graft across the physis, whereas all four dogs with no graft placed in tunnels demonstrated physeal arrest[29]. Guzzanti et al. noted cases of growth disturbance, however they were not common in rabbits[30]. Houle et al. compared tensioned grafts to no graft in 2-4 mm tunnels in rabbits, and found growth arrest or deformity in eight of eleven (73%) rabbits[31]. They concluded that the proximal tibia is most vulnerable, soft-tissue grafts are not protective, larger drill holes led to more deformity, and tunnels should be kept under 1% of the physeal area. These studies indicate that a non-tensioned graft may be protective, whereas a tensioned graft is not protective.

The risks of growth disturbance must be balanced with the risks of chondral and meniscal damage with a non-operative approach caused by knee instability. We performed a study at the Children's Hospital of Philadelphia of patients under 14 years old at the time of reconstruction and showed that patients with a delay of over 12 weeks to surgery were 4 times more likely to have irreparable medial meniscal tears, and 11 times more likely to have grade 2, 3 or 4 lateral femoral condylar chondral damage[32].

In an attempt to quantify the additional injuries sustained with delay in treatment, we performed a stochastic decision tree to mathematically create a prospective cohort study of every child in the USA[33]. The decision tree incorporated variability at each node and decision point. This predicted a decrease of 3760 medial meniscus tears and 7820 cartilage tears in skeletally immature patients with early surgery relative to a delay beyond 12 weeks. This study predicted that nearly $30 million a year would be saved in hospital charges in early rather than delayed ACL reconstruction.

Operative Techniques for ACL Reconstruction in Skeletally-Immature Patients:

The goals with operative treatment are to regain stability, protect the knee, and prevent chondral and meniscal injury. The traditionally accepted principles with ACL reconstruction in skeletally immature patients include the following: fixation should not cross the physis, if drill holes are placed across the physis, they should be centrally located and as small as possible, and tensioning a soft tissue graft across a physis should be avoided if large amount of growth remains[34].

Multiple techniques for operative management of ACL injuries in patients with wide open physes have been reported by various authors[27,35-41]. Primary repair of the ACL has had poor results with limited numbers and follow-up[2,42]. Ten of 11 patients reported in these studies had

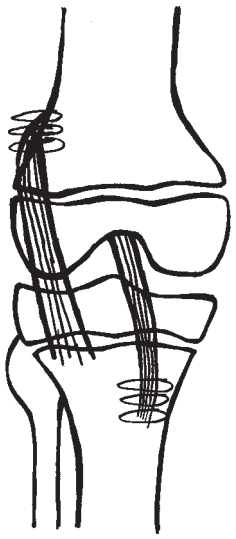

Figure 1. Schematic drawing of combined intra-articular and extra-articular reconstruction using an autogenous iliotibal band graft for ACL reconstruction with suture fixation at the distal femur and proximal tibia. Circles represent suture fixation.

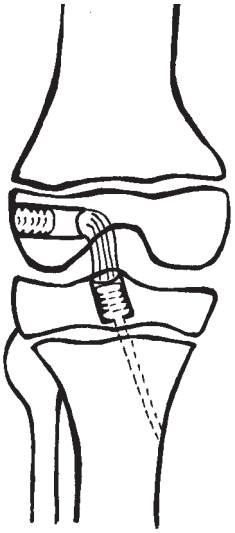

Figure 2. Schematic drawing of all-epiphyseal technique described by Lawrence et al. showing tunnel placement and interference screw fixation. All-epiphyseal femoral and tibial tunnel placement and fixation allows for independent tunnel placement and ACL femoral and tibial origin and insertion points.

subsequent laxity or giving way. Intra-articular extra-physeal techniques using combined intra-articular and extra-articular reconstruction using an autogenous iliotibal band graft are well documented with long-term follow-up and excellent functional results (Figure 1). Kocher et al. reported a series of 44 pediatric patients with an average post-operative follow-up of 5.3 years[43]. This technique avoids drilling tunnels across the physis and has demonstrated good outcomes. All but three patients with congenital limb deficiencies returned to cutting or pivoting sports. No patient had substantial angular deformity or growth disturbance. Only one patient in their series had an abnormal Lachman exam during follow-up. Two patients (4.5%) had a graft rupture and needed revision surgery at 4.7 and 8.3 years postoperatively. This technique has a non-anatomic nature for the intra-articular portion of the ACL. It reconstructs the anteriomedial bundle and not the posterolateral. It is important to note that the lateral extra-articular portion incorporates elements of the Losee procedure[44] that controls rotation and functionally substitutes for the lack of the posterolateral bundle.

ACL reconstruction utilizing all-epiphyseal tunnels have been performed since 1993 with few reports of growth arrest, limb length discrepancy, or significant side-to-side differences[6]. Anderson et al. reported a series of 12 skeletally immature patients with an average postoperative follow-up of 4.1 years[45]. This technique incorporates a quadrupled hamstring graft tensioned across epiphyseal tunnels in the distal femur and proximal tibia. The femoral tunnel extends parallel to the physis from the lateral epiphysis to the notch. The tibial tunnel extends from the anteromedial aspect of the tibial epiphysis to the joint. Femoral fixation is via an Endobutton (Acufex, Microsurgical, Inc, Mansfield, MA), and tibial fixation is via a screw and post. In their series, the limb length differences were within normal limits in all patients, and there was no differences found in femoral-tibial valgus angulation. Functionally, all patients were able to perform strenuous activities without pain at final follow-up. Although it has had excellent results, this technique is technically challenging and should only be performed by accomplished knee surgeons. There has been one reported case of distal femoral valgus angulation and limb length discrepancy associated with the use of an epiphyseal tunnel for a revision ACL reconstruction in an immature patient[46].

We developed an all-epiphyseal technique in 2007 (Figure 2), utilizing a limited-cut, low-dose radiation, intraoperative CT scan (O-arm, Medtronic, Inc, Minneapolis, MN) in order to confirm proper placement of the tunnels[47]. A femoral guide set at 95° is used for placement of a guide wire parallel to the physis to the center of the femoral ACL footprint. A retrograde drill (RetroDrill, Arthrex Inc, Naplex, FL) is then used to drill the all-epiphyseal tibial tunnel approximately 3 mm less than the distance from the tibial ACL footprint to the physis measured on the preoperative MRI. The O-arm is then used to assess the tibial drill hole and the femoral guide wire (Figure 3). The femoral tunnel is drilled using standard cannulated reamers with adequate placement of the guide wire. Tibial fixation is performed with a retrograde screw (RetroScrew, Arthrex Inc, Naplex, FL) and an interference screw is used for femoral fixation. Direct imaging of the femoral guide wire and tibial tunnels with respect to the femoral and tibial physes minimizes the risk of growth arrest.

Transphyseal drilling has been reported by many authors[48-50]. Tunnels with transphyseal techniques should be central when traversing the physis and should be as small as possible. When drilling across the physis, it is important to avoid generating a large amount of heat or leaving any bone fragments in the tunnel. Hand drilling across the physis to prevent heat necrosis and flushing the tunnel after drilling have been advocated. In a study of our patients, Aronowitz et al. revealed that in patients with appropriate bone age (13 in

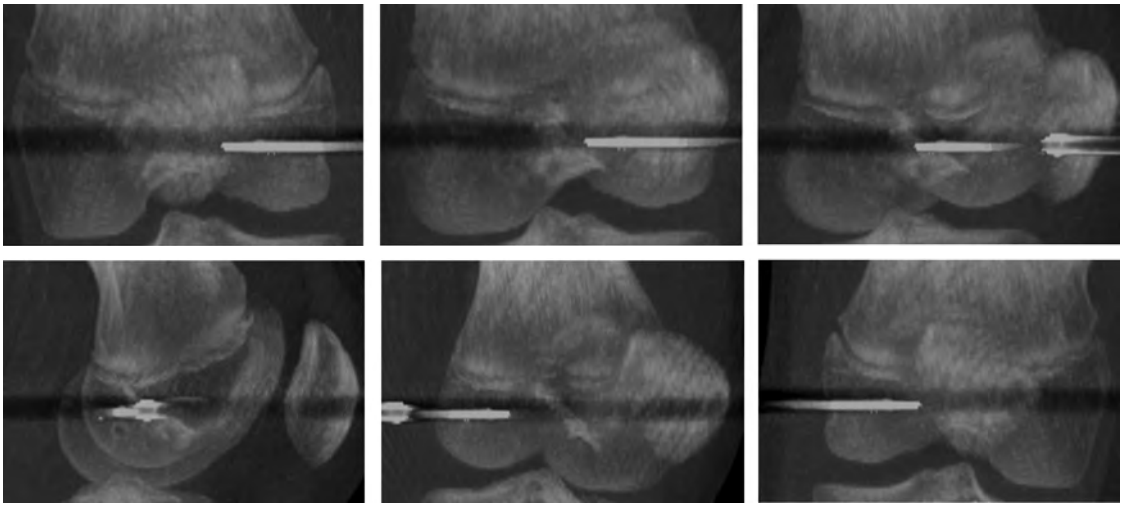

Figure 3. Intraoperative three-dimensional CT scan allows excellent visualization of the femoral and tibial tunnel placement relative to the physes. This allows the surgeon to evaluate tunnel placement in all planes to accommodate for the physes that undulate from front-to-back and side-to-side. The three-dimensional CT reconstruction shown above shows the guide pin in the distal femoral epiphysis rotating the image from left to right.

females and 14 in males), transphyseal techniques yielded no significant limb length discrepancy or deformities[48]. The risk to benefit ratio for patients with bone age of 13 in females and 14 in males is different than for patients with wide open physes. Sankar et al. showed in 276 patients that a transphyseal technique had similar results to the adult literature[49]. Another study showed that ACL tears with a concomitant medial collateral ligament (MCL) injury in children can be treated

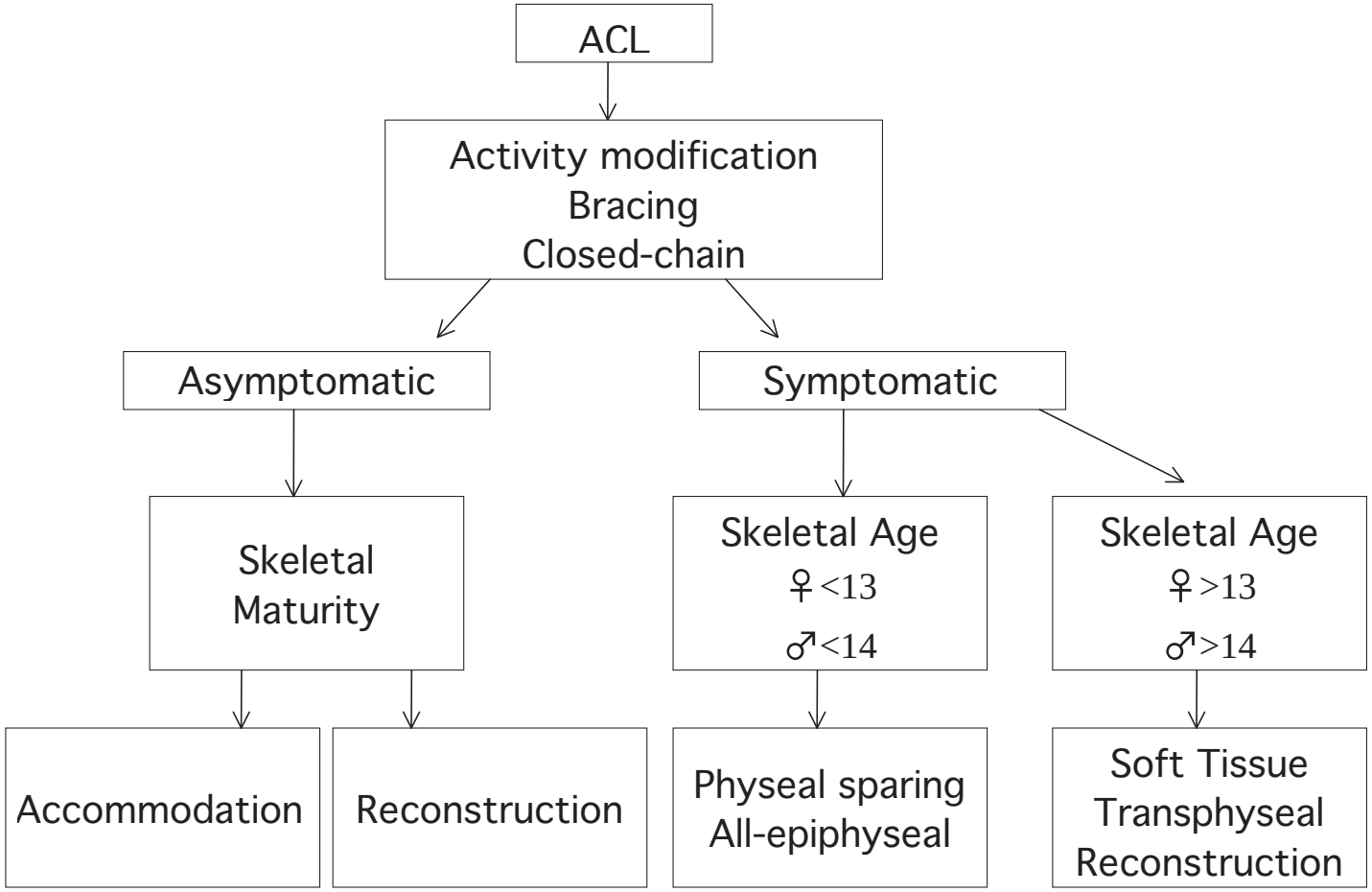

Figure 4. Our treatment algorithm for pediatric patients with ruptured ACL. After a trial of activity modification, bracing, and closed chain rehabilitation, symptomatic patients are candidates for surgical reconstruction. Prepubescent patients are at highest risk for growth disturbances, and physeal sparing techniques such as an all-epiphyseal or combined intra-articular and extra-articular reconstruction are warranted. Soft tissue transphyseal reconstruction is used on postpubescent patients.

the same as in adults with ACL reconstruction and MCL bracing[50]. The techniques used in these reports are not the techniques used for transphyseal reconstruction today with our understanding of the anatomic footprint of the ACL. To get the femoral graft in the correct position, the femoral tunnel has to be very eccentric in the distal femoral physis. Most of the successful reports used a transtibial technique with a very vertical graft that has been shown to not restore the normal biomechanics of the knee. Thus the question still remains: how safe are the eccentric transfemoral physeal tunnels used today? Although there have been good results reported in this age group with physeal respecting techniques, the potential damage that can be done is significant. A study by Wester et al. showed using a mathematical model of physeal damage after ACL reconstruction that angular deformity and limb length discrepancy in a 13-year-old male can be up to 21° valgus, 22° recurvatum, and 2.3 cm shortening[51]. This study highlights that care must be taken to avoid damage to the physis even in these older patients.

Treatment Algorithm

Physicians must balance the risks of early surgery with the risks of delay to surgery. Determinants of treatment options include: symptoms of recurrent instability and laxity, the degree of skeletal maturity, associated pathology such as chondral and meniscal damage, and compliance by the patient and family. Multiple methods are used to judge skeletal maturity. These include growth relative to family members, use of a growth chart with the presence of a growth spurt, time from onset of menses, Tanner staging, and bone age studies.

The traditional algorithm is to treat prepubescent patients with a delay in surgery and activity modification, bracing, and continued rehabilitation until skeletal maturity is reached, at which time a surgical reconstruction is performed. We believe that the recently published data on the detrimental effects of delay to surgery, as well as the development of physeal sparing techniques has tipped the scale in favor of early surgical reconstruction for prepubescent patients who remain symptomatic with pain and/or experience recurrent instability (Figure 4). In postpubescent patients, a transphyseal reconstruction is performed with a physeal respecting technique.

Conclusions:

There has been a recent increase in the incidence of ACL tears in skeletally immature patients[6]. Nonoperative treatments as well as primary repair have led to poor functional results[6]. There has been controversy in the literature about the decision to delay surgery versus performing an early ACL reconstruction. This decision must be made balancing the risks of each. Recent data quantifying the risks with delaying reconstruction as well as on new techniques that avoid the growth plates has many physicians leaning toward early reconstruction. The future will hopefully yield longer term follow-up with the new surgical techniques as well as a broader adaptation of prevention strategies for at-risk athletes.

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