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Management of ACL Injuries in Skeletally Immature Patients: Current Challenges and Treatment Options

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Abstract

Background

Injuries to the ACL are becoming increasingly common in pediatric and adolescent athletes, due to rising participation in high-demand sports. Managing ACL tears in patients who have not reached skeletal maturity is challenging because surgical reconstruction carries a risk of damaging open growth plates, while non-operative care may result in persistent instability and progressive joint damage.

Aim

This work aimed to sum up the latest research on the epidemiology, diagnostic considerations and treatment options for ACL in patients who have not reached skeletal maturity, with a particular focus on achieving a balance between restoring knee stability and protecting the growth plates.

Material and methods

This review draws on published clinical studies, epidemiological data, and systematic reviews, which are referenced throughout the text. The material covers findings on injury incidence, risk factors, the outcomes of non-operative and operative management, and the complication rates.

Results

ACL injuries represent up to 50% of knee sports injuries, with an increasing incidence among young athletes. Non-operative treatment often results in persistent instability, meniscal or cartilage damage, and early degenerative changes. Modern surgical techniques offer different risk profiles based on skeletal maturity. Reconstructive procedures can disrupt open growth plates, so performing surgery on patients who have not yet reached skeletal maturity is challenging. Therefore, accurately assessing skeletal maturity is crucial when deciding on the most suitable surgical approach.

Conclusions

ACL injuries in patients who are not fully grown require management that is tailored to skeletal maturity rather than chronological age. Non-operative treatment may only be acceptable in low-activity children who have been carefully selected. When chosen appropriately, surgical reconstruction can restore knee stability while minimizing growth-plate complications.

Key words: Pediatric ACL injury, pediatric ACL tear, pediatric ACL treatment, pediatric ACL reconstruction

Introduction

The anterior cruciate ligament (ACL), which runs from the femur to the tibia, plays a key role in maintaining knee stability [1,2]. Its femoral attachment is located on the posterior part of the medial surface of the lateral femoral condyle [3]. The ligament inserts anterolaterally onto the anterior tibial spine, blending with the anterior horn of the lateral meniscus [4]. The structure consists of two major fibers groups, known as the anteromedial and posterolateral bundles [5]. The main function of the ligament is the limitation of anterior translation of the tibia in relation to the femur. Furthermore, it plays a significant role in the regulation of knee hyperextension and regulating internal tibial rotation [2,6]. It also protects the meniscus by reducing the shear stresses caused by sport-related movements such as jump landings, directional pivots, and deceleration [6].

Unfortunately, the ACL is one of the most injured ligaments in the knee joint [7]. An injury to this ligament presents a significant clinical challenge in pediatric and adolescent patients who are active. Taking part in high-risk sports involving rapid cutting and pivoting movements, such as basketball, football, skiing and football increases the risk of injury [7, 8, 9]. Over the past twenty years, clinicians treating young athletes have noted a significant rise in the incidence of ACL tears [6,10]. This trend correlates with increased participation in professional sports, which has been associated with higher rates of ACL damage in skeletally immature patients [6,10,11,12]. Today's athletic practices, including year-round training, prolonged practice sessions and early specialization, expose young athletes to repetitive biomechanical stress [8,13].

A tear in the anterior cruciate ligament at a young age can be a life-changing incident. Injuries like these may lead to long-term health problems, such as knee osteoarthritis, which can affect participation in sports, cause ongoing pain, and difficulties with everyday activities [6,14,15]. The management of ACL tears in pediatric athletes is challenging and a topic of ongoing debate. It is very important to have discussions with the patient and their parents about the available treatment strategies, expectations, and individual goals [6,16]. Surgical intervention for ACL injuries in skeletally immature patients remains controversial, as conventional reconstruction techniques require drilling across open growth plates, which may result in growth disturbance. Up to now, there has been no universally accepted standard for the best way to treat ACL injuries in children. Surgical approaches are constantly improving, with the aim of balancing safety with effective restoration of knee stability [6].

Epidemiology

Most anterior cruciate ligament tears occur during athletic activities [6]. Some studies suggest that ACL injuries may constitute up to 50% of all knee-related sports injuries [17]. In the United States, it is estimated that there are approximately 100,000–200,000 cases of ACL injury per year [7,18]. Common risk factors for this type of injury include female sex and younger age, particularly during adolescence. The highest incidence is observed among individuals aged 18–35 years. The rate of ACL reconstruction in 12–13-year-olds (3.5 surgeries for every 100,000 people) was a lot lower than in 16–39-year-olds (85 surgeries for every 100,000 people). It should be noted that the true number of cases is underestimated by patients who were managed non-operatively [6,19]. Although ACL injuries associated with sports have been documented in children as young as five, available evidence suggests that ACL ruptures in individuals under 12 are not common [20,21]. In a retrospective study, only 3% of diagnosed ACL injuries occurred in patients aged 14 years or younger over a six-year period [22]. Interestingly, among pediatric athletes under 12 years old, males experience almost double the number of injuries compared with females. Another research reported favorable postoperative outcomes in 12

children aged 10–13 years who underwent ACL reconstruction, 10 of these patients were male [23]. In 13 studies, 73.2% of injured athletes were male [24]. One potential reason for the higher rate of ACL injuries in prepubescent boys is the different athletic involvement levels between the sexes. According to statistics, boys participate in organized sports more frequently than girls, resulting in greater overall exposure to athletic activities and, consequently, a higher risk of injury [9]. Notably, results show an increase in ACL injury rates in female athletes around puberty. As girls experience their growth spurt earlier than boys, the rapid elongation of their limbs and increased height and weight shift their center of mass and elevate mechanical stress on the knee [6,25]. In contrast, in that time boys develop more muscle mass, which helps to reduce the impact on ligaments such as the ACL [6]. Before puberty, the increased participation of boys in sports is likely to explain the higher frequency of injuries, whereas growth acceleration and physiological changes place female athletes at a higher risk [6,9,26]. After puberty, the pattern reverses and males aged 17–19 are more likely to sustain an ACL injury than females of the same age. This decreased risk in female athletes may partly reflect higher rates of sport discontinuation in post pubertal girls [9, 26].

Treatment options

The management of ACL injuries may be through operative or conservative approaches. There is no strict standard for treating these injuries in children. Each option has unique advantages and disadvantages, so treatment should be adapted to the patient's activity level, functional requirements, and personal goals [6,16]. Surgical treatment is generally considered when athletes are unable to continue playing their sport; instability interferes with daily activities, a meniscal tear can be repaired, or when multiple ligament injuries are present [6]. Due to the potential damage of open growth plates during reconstruction, operative management in patients who have not yet reached skeletal maturity is difficult, as it may cause growth-related complications such as limb length discrepancies or angular deformities [6,27]. On the other hand, conservative treatment in highly active adolescents can lead to subsequent meniscal or cartilage injury, accelerating degenerative joint changes, and contributing to long-term knee instability [22,28,29,30].

When managing ACL injuries in young athletes, it is essential to assess skeletal maturity. Although chronological age has historically been used to guide decision making in pediatric ACL management, it does not reliably reflect differences in skeletal development among children of the same age [16,31,32,33]. The most used method of estimating skeletal age is to compare an anteroposterior radiograph of the left hand and wrist with the relevant age-specific standards from the Greulich and Pyle atlas. Tanner staging, which requires clinicians to examine pubic hair distribution, breast development, or testicular volume, also has been shown to be both valid and reliable. In orthopedic practice, bone age assessment is generally preferred to Tanner staging because X-rays are easily accessible and provide objective information. This approach avoids concerns about the accuracy of Tanner staging. A radiographic assessment of the knee bone age may also be performed [6,16,32,34,35,36].

Non-surgical treatment

Non-operative treatment for ACL injuries usually involves wearing knee brace, undergoing a structured rehabilitation program, and avoiding athletic activities for an extended period [16,37]. This approach is usually recommended for patients who can follow strict limitations on physical activity. In some cases, clinicians may delay surgical intervention until skeletal maturity has been reached [6,32]. Although strengthening exercises combined with bracing can improve knee function, nonoperative approaches are rarely successful without strict activity restrictions [11]. Children who do not have surgery are more likely to have a poor outcome when they resume sport, including occurring instability and reduced satisfaction with their performance [27,38]. Radiographic signs of osteoarthritis may develop within 12 years of the initial injury [39,40,41]. Research shows that between 21% and 100% of pediatric ACL injuries are also

accompanied by meniscal tears [42]. Prolonging the surgical intervention for ACL reconstruction can result in an elevated possibility of meniscal injury, with the potential of initially reparable tears ultimately becoming irreparable ones. ACL and meniscal injuries in combination lead to worse long-term outcomes and increased risk of early osteoarthritis [28,40,41].

Surgical treatment

The primary goal of surgical management is to stabilize the knee while protecting the open growth plates. For younger patients, who are particularly sensitive to growth disturbances (particularly girls with a skeletal age under 11 and boys under 13, Tanner stages I–II), extraphyseal ACL reconstruction is generally preferred in order to avoid drilling tunnels across the physes [6,43,44,45]. In physeal-sparing techniques, the iliotibial band is used. The graft is placed superficially over the fibular collateral ligament, goes over the top of the femur, passes through the intercondylar notch and under the intermeniscal ligament. It is then secured to the periosteum of the proximal tibia and the lateral femur [46]. This method is known as an 'over-the-top' (OTT) approach and is often performed with lateral tenodesis [47]. This method is occasionally considered to be incorrect anatomically. However, research has shown that this method restores native constraint and is associated with low revision rates. These minimally invasive techniques preserve the hamstring insertion, allow for graft placement, and combine intra- and extra-articular procedures to improve rotational control and protect the graft [44,48,49].

All-epiphyseal ACL reconstruction offers the same benefits as physeal-sparing techniques plus the advantage of closely replicating the native ACL footprint [50]. Research shows that these procedures restore normal knee movement and reduce posterior joint contact stresses [48]. This approach has various variations, each with unique drilling and fixation techniques [50]. The first one includes outside-in epiphyseal tunnels, a quadrupled hamstring graft, suspensory fixation on the femoral side, and metaphyseal post or an epiphyseal suspensory device on the tibial side [38]. The second method also uses a hamstring graft but relies on retrograde-placed interference screws for fixation to avoid crossing the growth plates [51]. The third modification involves creating bone sockets and using cortical buttons for fixation to maximize graft-to-bone contact [52]. Some sources have reported a 16.5% complication rate, including graft rupture, limb-length discrepancy, arthrofibrosis, and subsequent meniscal tears. These are being used more with very young athletes, but more long-term data and close follow-ups are required [53].

Another surgical option is the partial transphyseal approach, in which the tunnel is created such that it passes centrally through the physis of the tibia while avoiding the physis of the femur [27,32,38]. For children with at least three years of growth remaining, partial transphyseal reconstruction can be considered. However, there is limited published evidence on this technique. In one study, around 21% of patients experienced growth disturbances, including valgus deformity. Among those with more than five years of growth remaining, the incidence of growth abnormalities increased to 67%. Graft failure occurred in around 8% [54]. These findings suggest that the youngest patients may not be ideal candidates for this approach. More research is needed to clarify which age groups are most suitable for partial transphyseal reconstruction [27,32,50,54].

Older patients near full skeletal maturity are generally suitable candidates for standard transphyseal anterior cruciate ligament reconstruction [6]. In this method, surgeons create small tunnels in a central position and insert grafts, such as hamstring autografts. The fixation is intentionally positioned away from the growth plates to reduce the likelihood of physeal injury [6,45,55]. Although this technique is generally considered safe, there is still a residual risk of growth-plate disturbance, and some patients may require additional procedures if growth abnormalities develop. In this age group, complications have been reported when bone blocks

cross the growth plates unintentionally, sometimes resulting in early physeal closure [6,32,50,56].

Discussion

ACL injuries in children and adolescents with open growth plates are difficult to manage. Non-operative treatment was traditionally the preferred option to avoid damage of the growth plates. Research suggests that it often causes knee instability, meniscus injury, early degenerative changes, particularly in young patients, and rarely leads to satisfactory outcomes in this population [6,8]. One study investigated 18 growing athletes without surgery after an ACL rupture. Only one child was able to return to their previous level of sport, while most showed limited functional performance [28]. In another work 80% of patients with an average age 11 years were initially treated nonoperatively. After four years, MRI showed 28.5% of knees had progressed meniscal damage and 3.6% developed new meniscal or cartilage lesions. Despite this, 88% of participants remained active [57]. A 2011 systematic review compared non-operative and surgical treatments, finding that non-operative management was often associated with persistent instability and progressive meniscal or cartilage damage. This often resulted in the need for delayed surgical intervention [29]. Only one study showed comparable rates of secondary injuries in the surgical and non-surgical groups. Additionally, strict activity limitations were highlighted as key to reducing the risk of further harm, with non-surgical care recommended for those with low activity levels who can adhere to these restrictions [31]. It was also found that using braces combined with structured rehabilitation enables skeletally immature patients to return to activity. Up to 65% of patients resumed sports before undergoing ACL reconstruction surgery. However, 10% of them experienced secondary meniscal injuries [29]. A 2014 prospective study of patients treated non-operatively found that 19,5% who remained active in pivoting sports, developed new meniscal tears. In addition, growth disturbances were identified, with 27.6% of cases requiring surgical correction [57].

Modern surgical strategies aim to balance the restoration of knee stability with the preservation of growth plates. A meta-analysis of 55 studies indicated that the risk of developing leg-length discrepancies or angular deformities following ACL reconstruction in children and adolescents is estimated at 2% [58]. One recognized complication of surgical treatment is graft failure. Studies report an average rerupture rate of 8.7%, which can occur from six weeks to 99 months after the initial procedure. Of those who experienced graft failure, 94.6% ultimately underwent revision surgery, either early on or when they reached skeletal maturity [59]. Another potential complication is growth disturbance, with reports showing that approximately 27.6% of affected patients had corrective surgery. Despite these concerns, successful results are generally observed following ACL reconstruction in skeletally immature patients [59]. Another systematic review detailed the types of growth disturbances seen in skeletally immature patients. Valgus changes were the most reported angular issue, likely due to tunnel positioning near the lateral distal femoral physis. In cases requiring surgical correction, technical errors were identified, such as bone plugs being fixed too close to the physis, tunnels being drilled too close to the distal femoral plate, and femoral tunnels being drilled at an excessively oblique angle [60]. Young athletes who return to sport after an anterior cruciate ligament reconstruction are at substantially increased risk of sustaining another ACL injury — around 30 to 40 times higher [7]. Research shows that, while 91% of young athletes who returned to sport, almost one-third suffered a second ACL injury, affecting either the reconstructed knee or the other knee [61].

Patients with less than 1 cm of remaining knee growth — generally boys of bone age 15–16 and girls of bone age 13–14 — have a very low risk of developing a clinically significant growth disturbance. In these cases, transphyseal technique is considered safe, as any physeal arrest at this stage is unlikely to result in significant deformity [62]. For younger patients, especially boys of bone age 13–14 and girls of bone age 11–12, physis-sparing reconstruction is an appropriate and frequently recommended approach. The preoperative screening should include

a skeletal age assessment of the left hand and imaging to determine the length of the lower limbs [50]. When selecting the most suitable treatment strategy for children with 1–5 cm of growth remaining and a notable risk of growth disturbance, multiple factors must be considered [50]. When more than 5 cm of growth remains, the potential impact of growth disturbance becomes significant. Consequently, a physeal-sparing ACL reconstruction is typically recommended. This group generally includes boys of bone age 12 years or younger, and girls of bone age 10 years or younger. Iliotibial band reconstruction is the most used technique as it results in good outcomes, with low graft failure rates and no noticeable growth-related complications in younger patients [42,49,50].

Determining skeletal maturity is essential for selecting the appropriate surgical technique. Chronological age is an unreliable indicator of biological development, so bone age assessment is preferred for its accuracy, accessibility, and objectivity. Using bone age allows clinicians to optimize surgical planning and reduce the risk of growth-related complications [45,50,62,63].

Conclusion

ACL injuries in patients who have not reached skeletal maturity present a complex and increasingly common challenge, largely due to the growing participation of young people in sports and other high-demand activities. Although conservative treatment may be suitable for low-activity children who have been carefully selected, evidence consistently shows that non-operative management in active patients leads to ongoing instability, progressive meniscal and cartilage injury, and an increased risk of early osteoarthritis. Modern surgical options, ranging from physeal-sparing to transphyseal techniques, enable the restoration of knee stability with minimal risk to the growth plates, provided that skeletal maturity is accurately assessed, and the appropriate method is chosen. With proper treatment and rehabilitation, most patients can successfully return to sport.

Disclosure

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