Intrasubstance Anterior Cruciate Ligament Injuries in the Pediatric Population

Abstract

Pediatric intrasubstance anterior cruciate ligament (ACL) tears have a significant epidemiologic impact as their numbers continue to grow globally. This review focuses on true pediatric intrasubstance ACL tears, which occur >400,000 times annually. Modifiable and non-modifiable risk factors include intercondylar notch width, ACL size, gender, landing mechanisms, and hormonal variations. The proposed mechanisms of injury include anterior tibial shear and dynamic valgus collapse. ACL tears can be associated with soft tissue and chondral defects. History and physical examination are the most important parts of evaluation, including the Lachman test, which is considered the most accurate physical examination maneuver. Imaging studies should begin with AP and lateral radiographs, but magnetic resonance imaging is very useful in confirming the diagnosis and preoperative planning. ACL injury prevention programs targeting high risk populations have been proven to reduce the risk of injury, but lack uniformity across programs. Pediatric ACL injuries were conventionally treated nonoperatively, but recent data suggest that early operative intervention produces best long term outcomes pertaining to knee stability, meniscal tear risk, and return to previous level of play. Current techniques in ACL reconstruction, including more vertically oriented tunnels and physeal sparing techniques, have been described to reduce the risk of physeal arrest and limb angulation or deformity. Data consistently show that autograft is superior to allograft regarding failure rate. Mean durations of postoperative therapy and return to sport were 7 ± 3 and 10 ± 3 months, respectively. These patients have good functional outcomes compared to the general population yet are at increased risk of additional ACL injury. Attempts at primary ACL repair using biological scaffolds are under investigation.

Keywords: *Anterior cruciate ligament, pediatric, pediatric intrasubstance anterior cruciate ligament tear, anterior cruciate ligament reconstruction, pediatric orthopedics*

MeSH terms: *Pediatrics, anterior cruciate ligament, magnetic resonance imaging*

Alexandr Aylyarov, Mikhail Tretiakov, Sarah E Walker, Claude B Scott, Khalid Hesham, Aditya V Maheshwari

Department of Orthopaedic Surgery and Rehabilitation Medicine, State University of New York (SUNY), Downstate Medical Center, Brooklyn, NY, USA

Address for correspondence: *Dr. Khalid Hesham, 450 Clarkson Ave, Box 30, Brooklyn, NY, USA 11203. E-mail: khalid.hesham@gmail.com*

Introduction

Pediatric intrasubstance anterior cruciate ligament (ACL) tears are of growing interest in the orthopedic and sports communities, with particular emphasis on prevention and surgical management of these injuries. Classically, the tibial eminence avulsion fracture has been considered the pediatric "equivalent" of the adult intrasubstance ACL tear. Recent literature, however, is pointing toward an increase incidence of a pediatric intrasubstance tear as well.[1,2] This review will focus on the "true" intrasubstance ACL tears in the pediatric age group.

Demographics

Incidence

The incidence of intrasubstance ACL tears in all age groups has been estimated at >400,000/year in the western literature.[1,2] In the pediatric population, two nationwide registries from Sweden and New Zealand found the annual incidence to be 65–144/100,000 for patients over the age of 10. Exceedingly, few tears were found in patients below the age of 10 in both studies.[3,4] A recent retrospective review of 20-year insurance claim data from a high income nation found a similar incidence of an average of 121/100,00 person-years, with an annual increase of 2.3%/year.[2] The incidence of intrasubstance ACL tears in Asian regions including India remains unknown.

Risk factors

Risk factors for pediatric intrasubstance ACL include non-modifiable and modifiable patient characteristics. Non-modifiable risk factors include anatomic considerations such as intercondylar notch

How to cite this article: Aylyarov A, Tretiakov M, Walker SE, Scott CB, Hesham K, Maheshwari AV. Intrasubstance anterior cruciate ligament injuries in the pediatric population. Indian J Orthop 2018;52:513-21.

Access this article online

Website: www.ijoonline.com

DOI: 10.4103/ortho.IJOrtho_381_17

Quick Response Code:

width, ACL size, female gender.[5] Modifiable risk factors include "cutting" sports, landing mechanics, and hormonal variations during the menstrual cycle.[6]

Gender bias

Females were found to have a significantly increased ACL tear rate relative to males, especially when they were younger than 17 years.[2] Overall female incidence was 129 tears per 100,000 patient years, peaking at age 16 with 392/100,000. Male incidence was 114/100,000 overall, peaking at age 17 with 492/100,000.[2] Multiple mechanisms have been proposed to explain this [Table 1].[5-8]

Genetics

Both protective and harmful genetic factors in ACL ruptures have been scrutinized, particularly variants of the collagen-encoding genes *COL1A1*, *COL3A1*, and *COL5A1*. While some articles have mentioned an association between ACL rupture in adults and presence of polymorphisms, two recent review articles were unable to conclusively link any specific gene to an increased risk of ACL rupture.[5-8]

Financial impacts

Pediatric ACL reconstructions in New York State increased from 18/100,000 population in 1990, to 51/100,000 population in 2009.[9] The long term impact of pediatric ACL tears is incompletely understood. Within 14 years of sustaining an ACL tear, about 78% of adults had radiographic evidence of arthritis in the affected knee.[10,11] The link between meniscal damage and development of arthritis is although well documented, however long term followup of adults with ACL injury has not addressed the association between ACL tears and the development of symptomatic arthritis.[12] In addition, long term costs associated with ACL reconstruction in adults may be as high as $38,000.[13] Pediatric-specific data on costs and long term morbidity from intrasubstance ACL tears, especially symptomatic arthritis requiring treatment, still remains incomplete. However, an association has been described between delayed operative management and meniscal tears.[14]

Table 1: Gender difference in risk factors for anterior cruciate ligament tear (adapted with permission from Orthobullets.com)

Risk Factor	Pertinent Details
Anatomic	Decreased intercondylar notch width (impingement on ACL)[5]
	Smaller ACL[5]
	BMI[63]
	Hypermobility[63]
Biomechanical	Increased knee valgus during landing[6]
	Increased knee extension during landing[6]
	Fatigue resistance[64]
Neuromuscular	Lower hamstring: quad ratio[6]
	Lower hamstring recruitment[6]
	Weaker core stability[65]
Hormonal	Preovulatory phase of menses[66]
	Oral contraceptives-protective[63,66]
Genetics	COL5A1-protective[5]

ACL=Anterior cruciate ligament

Pathomechanics

Anatomy

The ACL is a strong band of connective tissue traveling from the posteromedial aspect of the lateral femoral condyle to the anterior tibial plateau. It is comprised two functional bundles, the anteromedial bundle (AM) and the posterolateral (PL) bundle, named for their tibial insertions. Historically, the AM bundle was considered the main functional portion, but recently, more focus is being placed on the PL bundle and its effect on rotational stability. The AM bundle is tight in flexion and contributes primarily as a restraint to anterior translation of the tibia, while the PL bundle is tightest in extension.[15]

The ACL receives its blood supply from the middle geniculate artery, a branch of the popliteal artery.[16] Tibial nerve branches are responsible for innervation of the ligament, mainly serving proprioceptive and vasomotor sensory functions. There are essentially no pain fibers within the ACL, thus pain after an ACL tear develops only after hemarthrosis development within the knee.[17]

Collectively, the physes surrounding the knee joint are the most active of any joint in the body. The distal femoral physis contributes to over 37% of total limb length, with the proximal tibial physis contributing to an additional 25%.[1] Thus, pediatric ACL tears present a challenge, as iatrogenic damage to an open physis can lead to severe sequelae.

Mechanism of injury

Acute ACL injuries are most often noncontact injuries, during lateral pivoting, landing, or deceleration maneuvers, with the knee in shallow flexion and the foot planted.[18] These mechanisms lead to two predominant theories of ACL loading-anterior tibial shear and dynamic valgus collapse. Dynamic valgus collapse is theorized to be a greater issue in female.[19]

Associated injuries

Both soft tissue and osteochondral injuries have been described to have an association with pediatric ACL tears.[20-22] Impaction forces at the time of injury lead to bony edema secondary to trabecular microfracture. This is classically seen in the middle third of the lateral femoral condyle and the posterior third of the lateral tibial plateau.[20,23] While it is unclear whether these findings independently lead to long term sequelae, subchondral changes can persist on magnetic resonance imaging (MRI) for several years after injury.[23,24]

Soft tissue injuries, including medial meniscus, lateral meniscus, and medial collateral ligaments (MCL) injuries can all have significant long term effects if they are unrecognized.[25] The percentage of associated meniscal pathology varies by study, with acute ACL tears having a higher associated lateral meniscal injury and medial meniscal pathology having a higher association with chronic tears.[26] Furthermore, successful repair of ACL-related meniscal injury is less successful with an increased delay in surgery.[27] Combined pediatric ACL/MCL tears have few reports in the literature, but valgus instability may result if MCL injury is missed.[28,29]

Diagnosis

Diagnosis of ACL tears begins with a thorough history, including possible risk factors, mechanism, and duration of symptoms. Acute ACL injuries are often described as having a distinct "pop," with a subsequent feeling of knee instability. There is a successive pain after an effusion develops. Between 47% and 65% of pediatric patients will develop a posttraumatic hemarthrosis.[29]

A subsequent physical examination should begin with an examination of the uninjured side. This may calm anxious pediatric patients through demonstration of maneuvers, while also establishing patient-specific "normal." Inspection and palpation of the joint should be performed to assess for effusion as well as specific areas of tenderness. The range of motion may be limited by anxiety and pain, but gentle active and passive evaluation is necessary to assess for accompanying meniscal pathology; the patient should also be evaluated for hypermobility (via Beighton score) and associated injuries. The Lachman test, anterior drawer test, and pivot shift test are all specific tests utilized to diagnose ACL tears. With a sensitivity of 85% and specificity of 94%, the Lachman is considered as the most accurate test. While the pivot shift test has a very high specificity (98%), the poor sensitivity (24%) as well as the reproduction of knee instability make it a more limited test in the pediatric population.[30-33] The knee arthrometer (e.g., KT-1000) is an objective tool that can be used to assess the amount of tibial translation compared to the healthy joint.[34]

Imaging studies should begin with standard anteroposterior and lateral radiographs. This can allow for the evaluation of tibial eminence fractures, status of the physis, and any anatomic variations. Often, a history and physical examination is all that is necessary to diagnose an ACL injury. However, in a pediatric patient where an accurate examination is difficult, and in a patient with an equivocal examination, MRI can be utilized to aid in diagnosis [Figure 1]. It is also helpful in preoperative planning, as it can also show other associated soft tissue injuries.[35]

Management

Prevention

In response to an increase in pediatric ACL injuries and recognition of their importance, particularly in female

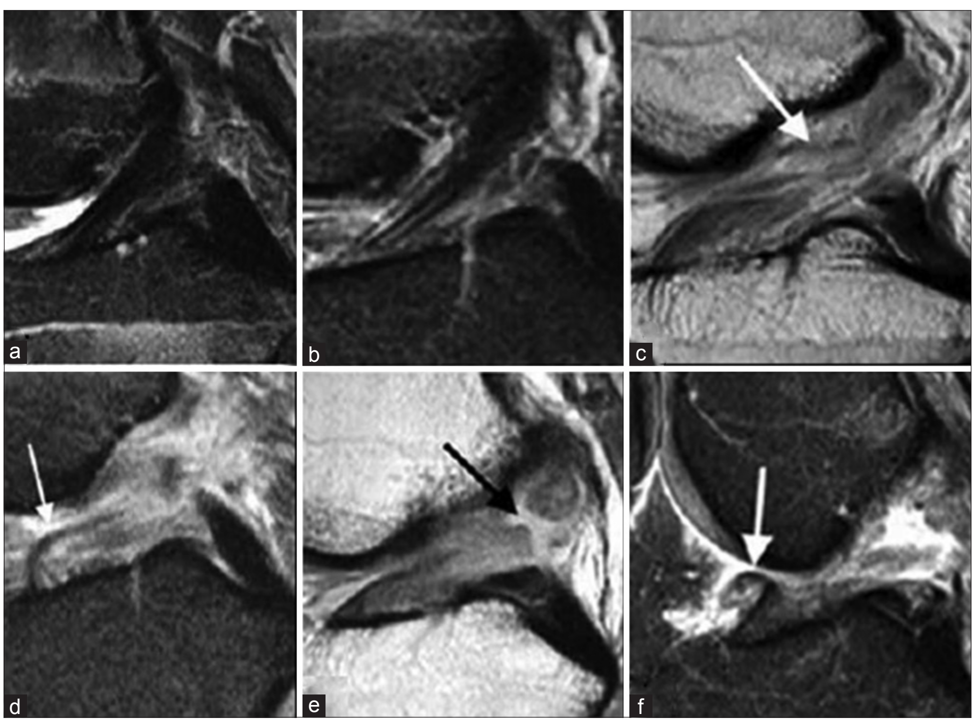

Figure 1: Proton-density magnetic resonance imaging (a-f) with fat saturation (except c and e) showing the spectrum of anterior cruciate ligament injuries in the sagittal plane in pediatric patients aged 13-16 years (adapted from Jaremko *et al.*) (a) intact anterior cruciate ligament; (b) thin, but intact anterior cruciate ligament; (c) surgically confirmed high grade partial anterior cruciate ligament tear with lax fibers; (d) full-thickness midsubstance anterior cruciate ligament tear with some intact fibers near the tibial attachment (*arrow*); (e) full-thickness tear; (f) full-thickness tear with anteriorly flipped distal ligament fibers (*arrow*) and anterior tibial translation

athletes, there has been an increase in neuromuscular ACL injury prevention programs. These programs target modifiable risk factors, including biomechanical patterns and neuromuscular functional changes.[36] While ACL prevention programs have been accepted as effective in reducing primary injury, there are limited data on the uniformity of these programs. Components of these prevention programs include: balance, plyometrics (jump training), strength, agility, and stretching.[37] In addition, there is a discrepancy between the frequency and the duration that athletes perform these exercises. A metaanalysis performed by Taylor *et al*.[36] included 13 studies on ACL injury prevention programs, demonstrating that there was a statistically significant decrease in all ACL injuries (odds ratio [OR]: 0.61, 95% confidence interval [CI]: 0.44–0.85) and noncontact ACL injuries (OR: 0.35, 95% CI: 0.23–0.54) post training. Currently, there is no defined program composition for ACL injury prevention; however, it was noted that balance training– unless performed to correct other lower extremity biomechanics[38] did not demonstrate a decrease in OR of injury, whereas a combination of agility and strength training demonstrated beneficial results.[37]

Nonoperative management

Until recently, pediatric ACL tears were treated by limiting activity and sports play, bracing, and extensive rehabilitation due to the concerns of physeal arrest, limb length discrepancy or angular deformity after reconstruction. However, data specific to this population with nonoperative treatment demonstrates an increased risk in symptomatic medial meniscal tears, cartilaginous injury, continued laxity/instability, and an inability to return to prior level of play.[39] The preferred intervention has shifted recently toward early operative reconstruction due to these reasons.

Risk factors associated with the pediatric population in regards to meniscal and cartilaginous injuries in ACL deficient knees are increased age, male gender, one or more episode of instability, and an increased delay for surgery.[22,38,40,41] Anderson and Anderson reported that delayed ACL reconstruction increased the risks of secondary meniscal and chondral injuries in children.[14] Of particular concern is an increase in bucket handle meniscus tears which have a poor prognosis after surgical repair, therefore predisposing these patients to future arthritic changes of the knee.[14,21] In addition, patients treated nonoperatively or with delayed treatment typically had more instability and laxity with an inability to return to prior level of activity or sports than patients treated with early surgical intervention <12 weeks.[39] These outcomes have led to the belief that early recognition and intervention of a pediatric ACL injury is necessary.

Operative management

Overview and technical considerations

Figure 2 demonstrates the currently preferred treatment algorithm for ACL reconstructions.[1] A variety of techniques are available depending on the patient's skeletal maturity, including physeal sparing, partial physeal, and transphyseal [Table 2].[1]

The transphyseal technique involves traversing both the tibial and femoral physis with a graft. Growth disturbance or angular deformity were only demonstrated when a method of fixation was passed across the physis, i.e., bone plug, staple, and screw. Considerations regarding the radius of the graft tunnel and drill angle are made when sizing and positioning the graft to decrease the possible risk of physeal damage. An increase in deformity is noted when >7% of the total physeal volume is involved while preparing the tunnel. A decrease from an 11 mm to

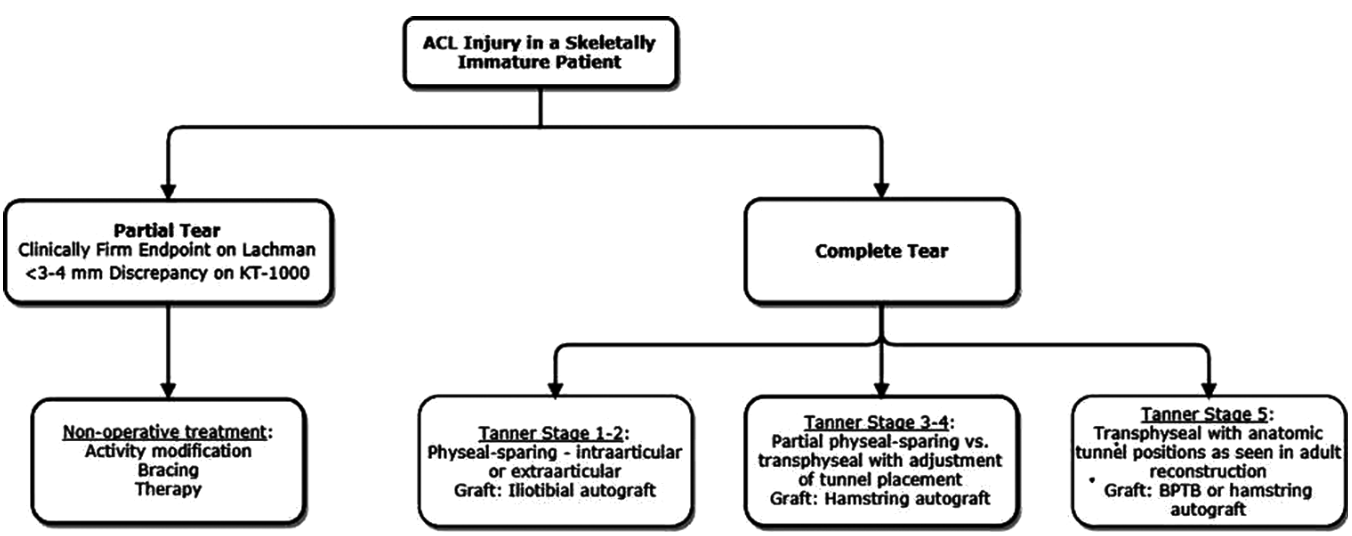

Figure 2: Algorithm for treatment of skeletally immature patients with either partial or complete anterior cruciate ligament tear (Adapted with permission from Fabricant *et al.*)

Table 2: Outcomes of anterior cruciate ligament reconstruction in pediatric patients using all-epiphyseal, extraphyseal, and transphyseal techniques (adapted with permission from Fabricant *et al*.)

Technique	Study	Number of patients	Mean age (years)	Followup (months)	Graft	Re-injury	Re-operation	Return to previous level of activity	Mean KT-1000 difference	Compli-cations
All epiphyseal	Anderson *et al*., 2003[60]	12	13.3	49.2	Hamstring	NR	NR	NR	1.5 mm	NR
	Guzzanti *et al*., 2003[61]	8	11.2	69.2	Hamstring	NR	NR	NR	1.8 mm	NR
	Cordasco *et al*., 2016[62]	23	12.2	32	Hamstring	4.3%	8.7%	96%	0.9 mm	NR
	Wall *et al*., 2017[63]	27	11.4	36.0	Hamstring	11%	15%	81%	NR	48%
Extraphyseal	Kocher *et al*., 2006[64]	44	10.3	63.6	Iliotibial band	NR	4.5%	62.5%	NR	NR
	Bonnard *et al*., 2011[65]	56	12.2	66.0	Bone -Tendon -Bone	5.4%	NR	62.5%	37.5% patients had 3-5 mm	NR
	Koch *et al*., 2014[66]	12	12.1	54	Hamstring	15.4%	23%	NR	1.5 mm	NR
	Cassard *et al*., 2014[49]	28	13	33.6	Hamstring	7.1%	NR	100%	NR	NR
Transphyseal	McIntosh *et al*., 2006[67]	16	13.5	41.1	Hamstring	12.5%	43.8%	87.5%	NR	NR
	Kocher *et al*., 2007[68]	59	14.7	43.2	Hamstring	NR	3%	NR	NR	Arthro-fibrosis 5.1%
	Liddle *et al*., 2008[69]	17	12.0	44.0	Hamstring	NR	NR	NR	None	Superficial infection 5.9%
	Courvoisier *et al*., 2011[70]	37	14.0	36.0-median	Hamstring	NR	13.5%	NR	1 mm	NR
	Kumar *et al*., 2013[71]	84	11.3	72.3	Hamstring	1.2%	NR	NR	NR	NR
	Schmale *et al*., 2014[72]	29	14	48	Hamstring or allograft	13.7%	38%	41%	NR	40%
	Calvo *et al*., 2015[73]	27	13	10.6	Hamstring	11%	14.8%	89%	2.58	NR

NR=Not reported

Table 3: Graft selection in reference to surgical technique, pros and cons

Graft	Surgical technique primarily used in	Pros	Cons
Iliotibial band	Kocher/micheli technique-physeal sparing-intraarticular and extraarticular	Decreased risk of rupture, decreased risk of growth disruption	Not anatomic, risk soft tissue tether on growth plate
Hamstring autograft	Anderson technique-transepiphyseal technique	Anatomic tunnel placement, decreased risk of rupture	Donor site morbidity, risk of soft tissue tether on growth plate
Hamstring allograft	Anderson technique/standard ACL reconstruction	Less donor site morbidity	Increased rupture risk-4 times that of autograft, risk of soft tissue tether on growth plate
Bone patella tendon bone autograft	Standard ACL reconstruction	Anatomic tunnel placement, decreased risk of rupture	Can only be used with patients of tanner stage 5 due to risk of physeal bar/arrest at site

ACL=Anterior cruciate ligament

6 mm diameter graft decreases physeal percentage from 7.8% to 2.3%, and a more vertically placed tunnel also decreases physeal damage by approximately 0.2% for every 5° angular increase. Thus, recommendations are more central and vertically placed, and a smaller diameter tunnel specific to pediatric patients.[1]

Partial physeal techniques involve sparing of either the tibial or femoral physis, recommended for use on Tanner stages I-V.[1] The graft choice is primarily by surgeon preference; however, the autologous hamstring is most often used. It has been shown that allograft use is associated with a higher rate of failure.[42]

The physeal sparing technique is suggested for use in Tanner stage I or II patient.[1] It utilizes an all epiphyseal trajectory of drilling or an extraarticular over the top method of fixation. The over the top method is performed by harvesting the middle one-third of the iliotibial band proximally, leaving an attachment to the Gerdy tubercle distally. This graft is then brought through the knee posteriorly and under the intrameniscal ligament anteriorly on the tibia. Fixation of the graft is performed by suturing it to the intermuscular septum and periosteum on the femoral side and the periosteum on the tibial side. Different physeal sparing techniques are demonstrated in Figure 3.

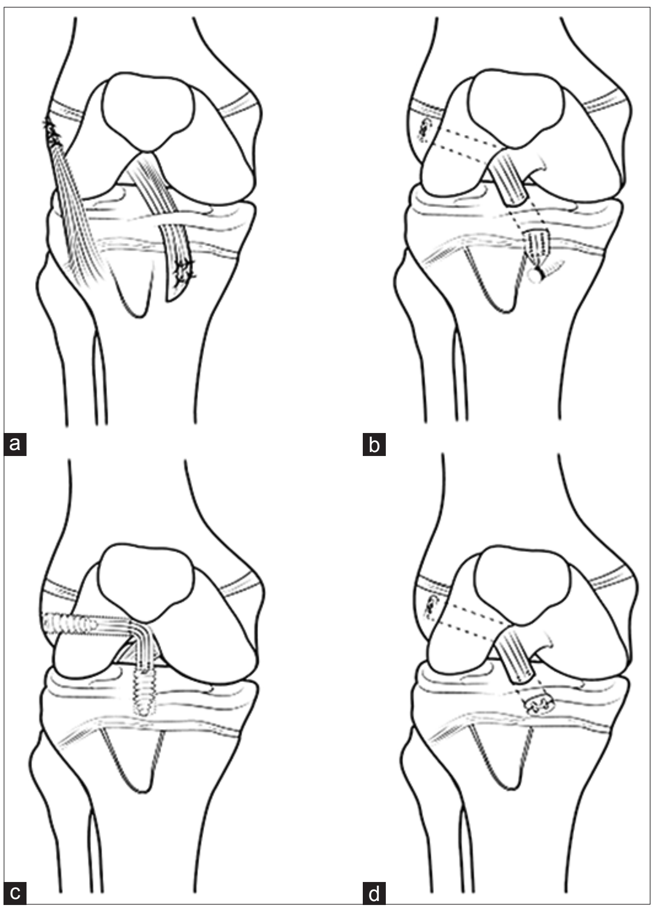

Figure 3: Diagrammatic representation of physeal sparing techniques for anterior cruciate ligament reconstruction in skeletally immature patients (Reproduced with permission from Fabricant *et al.*). (a) Kocher technique combines intraarticular with extraphyseal fixation. (b) Anderson technique is intraarticular both for femur and tibia, extraphyseal fixation on the tibia. (c) Ganley technique involves intraarticular all epiphyseal fixation utilizing interference screws. (d) Cordasco-Green utilizes intraarticular all epiphyseal with suspensory fixation

Graft selection

As described above under technical considerations, various surgical techniques favor specific graft choices; however, others leave room for surgeon preference. Table 3 demonstrates the graft choices in relation to the surgical techniques as well as the pros and cons for specific graft choices. Current literature demonstrates favorable outcomes for autograft selection of iliotibial band, hamstrings, or bone-patella tendon- bone. Allograft hamstring selection demonstrated an unacceptable risk for rupture, four times the rate of hamstring autograft.[42] Occasionally, autograft hamstring tendons may be very small in this population and may need to be augmented with allograft.[43]

Postoperative rehabilitation and return to sports

Postoperative rehabilitation

Postoperative ACL rehabilitation is focused on closed-chain, progressive exercise. Mean duration of physical therapy was 7 ± 3 months with a mean time to return to sport of 10 ± 3 months.[44] Accelerated rehabilitation programs (19 weeks) were found to have similar results in knee laxity, patient satisfaction, clinical assessment, and function as compared to nonaccelerated (32 weeks) programs.[45]

Return to sports

Return to sport generally is recommended after completing a postoperative rehab course of approximately 6 months. While the majority of patients returned to sports, on an average, they participated in fewer sports postoperatively. In the study by Dekker *et al*.[44] there was 32% prevalence of a second ACL injury either ipsilateral, contralateral or both. The only factor noted to place the patient at an increased risk for repeat injury was early return to sport <6 months. No clinical significance was noted with graft type.

Outcomes

ACL reconstruction with the use of autograft has become the gold standard for treating ACL tears in the young and active population.[46-48] Return to sport rates after ACL reconstruction are noted to be high, ranging from 80% to 100% as noted in Table 2, without the continued instability noted in patients treated nonoperatively. Cassard *et al*.[49] noted that Lysholm Knee scores in patients who have undergone an ACL reconstruction ranged from 85 to 100 which is similar to that of a population of healthy knees. A recent metaanalysis of 53 studies of ACL reconstruction in skeletally immature individuals found an overall rate of growth disturbance of approximately 2.6%.[50] The authors did not find a statistically significant difference between physeal-sparing and physeal-crossing techniques for growth disturbance, which they defined as a leg length difference of >1 cm or an axis deviation (varus, valgus or recurvatum) of >3°. Physeal-sparing techniques were associated with decreased postoperative complications;

however, the authors acknowledged that the metaanalysis was limited by a wide variability of outcome reporting among the individual studies. However, patients who undergo ACL reconstruction still have a relatively high rate of premature OA when compared to the general population.[51] This is hypothesized to be associated with the loss of the native biomechanics and proprioception of the ACL after reconstruction. In addition, there is a higher risk of rupture in the ipsilateral, contralateral or bilateral knee in comparison to an adult.[44] In summary, due to minimal findings of limb length discrepancy, angular deformity, continued instability, or inability to return to play, reconstruction of ACL injuries in the skeletally immature patient is currently the treatment option of choice.

Anterior cruciate ligament repair

Recently, there has been increased interest in ACL repair as well.[52,53] ACL repair, as compared to reconstruction, is believed to allow for some conservation of the native biomechanics and proprioception of the ligament. However, ACL repair is far from a new concept. The first described ACL repair in print was described by Robson in 1895. Robson described a suture repair of the ACL and PCL in a minor who was noted to walk without a limp and continue in his arduous occupation after 6 years followup.[54] In the 1930s to 50s pioneers such as Palmer and O'Donoghue described early ACL suture repair through bony tunnels.[55] All of these techniques stressed the importance of immobilization, usually for 4–6 weeks with the knee in 30° of flexion. In the 1980s two randomized clinical trials compared ACL suture repair against nonoperative management.[47,56] Although there were some noted differences, such as the repair group showing overall greater stability and preservation of menisci, both studies reported no significant difference between repair and nonoperative management in patient function and satisfaction. As a result, greater emphasis was placed on augmenting repair with graft, such as iliotibial band and BPTB. Overtime, these augmentation procedures transformed into reconstructions without the need for ACL repair.

One of the probable reasons that ACL repair failed in the past is due to repair site gapping. Even with meticulous suture repair, midsubstance tears are bound to have micro gapping.[52] Research over the last decade has been fierce in developing a collagen scaffold, impregnated with cells and growth factors to allow for ligamentous healing within the joint.

Currently, the only forms of ACL tears amenable to repairs are those that have avulsed off either at the proximal or distal ends of its origin. It is estimated that roughly 10% of ACL tears are avulsed from the femoral origin. In these cases, if the majority of the ACL remnant is found to be of viable tissue intraoperatively, an ACL repair through femoral and tibial drill holes can be attempted. We believe that in a specific population of pediatric patients with femoral avulsions of the ACL, an arthroscopic ACL repair with Fibertape augmentation can be an effective means of treatment with good functionality and the possibility of a decreased incidence of premature OA.[57,58]

Future Directions

Analyzing long term sequelae of ACL tears and the consequences of different repair and reconstruction techniques would greatly improve strategies for management. Animal models exploring the use of mesenchymal stem cells or mesenchymal progenitor cells demonstrated accelerated healing.[59] Gene therapy and tissue engineering are some key areas of research in ACL management. A collagen-silk composite scaffold was found to have sufficient mechanical support similar to the properties of the native ACL. Longer term animal studies, as well as human trials, are necessary.[58] Standardization of exercise regime in the prevention aspect is also important.

Conclusions

Pediatric intrasubstance ACL tears are increasing in incidence, particularly among female athletes. Numerous programs promote ACL tear prevention such as proprioceptive training and hamstring activation exercises in combination with strength training. Nonoperative management has been largely supplanted by operative management, with a variety of techniques including physeal-sparing and transphyseal reconstruction.

Financial support and sponsorship

No financial support or sponsorship was utilized for any aspect of this study.

Conflicts of interest

There are no conflicts of interest.

References

1. Fabricant PD, Jones KJ, Delos D, Cordasco FA, Marx RG, Pearle AD, *et al.* Reconstruction of the anterior cruciate ligament in the skeletally immature athlete: A review of current concepts: AAOS exhibit selection. J Bone Joint Surg Am 2013;95:e28.
2. Beck NA, Lawrence JT, Nordin JD, DeFor TA, Tompkins M. ACL tears in school-aged children and adolescents over 20 years. Pediatrics 2017;139. pii: e20161877.
3. Nordenvall R, Bahmanyar S, Adami J, Stenros C, Wredmark T, Felländer-Tsai L, *et al.* A population-based nationwide study of cruciate ligament injury in Sweden, 2001-2009: Incidence, treatment, and sex differences. Am J Sports Med 2012;40:1808-13.
4. Gianotti SM, Marshall SW, Hume PA, Bunt L. Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. J Sci Med Sport 2009;12:622-7.
5. Griffin LY, Albohm MJ, Arendt EA, Bahr R, Beynnon BD, Demaio M, *et al.* Understanding and preventing noncontact anterior cruciate ligament injuries: A review of the hunt valley II meeting, January 2005. Am J Sports Med 2006;34:1512-32.

6. Renstrom P, Ljungqvist A, Arendt E, Beynnon B, Fukubayashi T, Garrett W, *et al.* Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts statement. Br J Sports Med 2008;42:394-412.
7. Kaynak M, Nijman F, van Meurs J, Reijman M, Meuffels DE. Genetic variants and anterior cruciate ligament rupture: A systematic review. Sports Med 2017;47:1637-50.
8. John R, Dhillon MS, Sharma S, Prabhakar S, Bhandari M. Is there a genetic predisposition to anterior cruciate ligament tear? A systematic review. Am J Sports Med 2016;44:3262-9.
9. Dodwell ER, Lamont LE, Green DW, Pan TJ, Marx RG, Lyman S, *et al.* 20 years of pediatric anterior cruciate ligament reconstruction in New York state. Am J Sports Med 2014;42:675-80.
10. Murray MM. Current status and potential of primary ACL repair. Clin Sports Med 2009;28:51-61.
11. Kessler MA, Behrend H, Henz S, Stutz G, Rukavina A, Kuster MS, *et al.* Function, osteoarthritis and activity after ACL-rupture: 11 years followup results of conservative versus reconstructive treatment. Knee Surg Sports Traumatol Arthrosc 2008;16:442-8.
12. Meunier A, Odensten M, Good L. Long term results after primary repair or non-surgical treatment of anterior cruciate ligament rupture: A randomized study with a 15-year followup. Scand J Med Sci Sports 2007;17:230-7.
13. Mather RC 3rd, Koenig L, Kocher MS, Dall TM, Gallo P, Scott DJ, *et al.* Societal and economic impact of anterior cruciate ligament tears. J Bone Joint Surg Am 2013;95:1751-9.
14. Anderson AF, Anderson CN. Correlation of meniscal and articular cartilage injuries in children and adolescents with timing of anterior cruciate ligament reconstruction. Am J Sports Med 2015;43:275-81.
15. Petersen W, Zantop T. Anatomy of the anterior cruciate ligament with regard to its two bundles. Clin Orthop Relat Res 2007;454:35-47.
16. Toy BJ, Yeasting RA, Morse DE, McCann P. Arterial supply to the human anterior cruciate ligament. J Athl Train 1995;30:149-52.
17. Schutte MJ, Dabezies EJ, Zimny ML, Happel LT. Neural anatomy of the human anterior cruciate ligament. J Bone Joint Surg Am 1987;69:243-7.
18. Boden BP, Dean GS, Feagin JA Jr., Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. Orthopedics 2000;23:573-8.
19. Quatman CE, Hewett TE. The anterior cruciate ligament injury controversy: Is "valgus collapse" a sex-specific mechanism? Br J Sports Med 2009;43:328–35.
20. Jaremko JL, Guenther ZD, Jans LB, Macmahon PJ. Spectrum of injuries associated with paediatric ACL tears: An MRI pictorial review. Insights Imaging 2013;4:273-85.
21. Millett PJ, Willis AA, Warren RF. Associated injuries in pediatric and adolescent anterior cruciate ligament tears: Does a delay in treatment increase the risk of meniscal tear? Arthroscopy 2002;18:955-9.
22. Dumont GD, Hogue GD, Padalecki JR, Okoro N, Wilson PL. Meniscal and chondral injuries associated with pediatric anterior cruciate ligament tears: Relationship of treatment time and patient-specific factors. Am J Sports Med 2012;40:2128-33.
23. Pai DR, Strouse PJ. MRI of the pediatric knee. AJR Am J Roentgenol 2011;196:1019-27.
24. Papalia R, Torre G, Vasta S, Zampogna B, Pedersen DR, Denaro V, *et al.* Bone bruises in anterior cruciate ligament injured knee and long term outcomes. A review of the evidence. Open Access J Sports Med 2015;6:37-48.
25. Stevens KJ, Dragoo JL. Anterior cruciate ligament tears and associated injuries. Top Magn Reson Imaging 2006;17:347-62.
26. Hagino T, Ochiai S, Senga S, Yamashita T, Wako M, Ando T, *et al.* Meniscal tears associated with anterior cruciate ligament injury. Arch Orthop Trauma Surg 2015;135:1701-6.
27. Chhadia AM, Inacio MC, Maletis GB, Csintalan RP, Davis BR, Funahashi TT, *et al.* Are meniscus and cartilage injuries related to time to anterior cruciate ligament reconstruction? Am J Sports Med 2011;39:1894-9.
28. Sankar WN, Wells L, Sennett BJ, Wiesel BB, Ganley TJ. Combined anterior cruciate ligament and medial collateral ligament injuries in adolescents. J Pediatr Orthop 2006;26:733-6.
29. Stanitski CL, Harvell JC, Fu F. Observations on acute knee hemarthrosis in children and adolescents. J Pediatr Orthop 1993;13:506-10.
30. Bach BR Jr., Warren RF, Wickiewicz TL. The pivot shift phenomenon: Results and description of a modified clinical test for anterior cruciate ligament insufficiency. Am J Sports Med 1988;16:571-6.
31. Gurtler RA, Stine R, Torg JS. Lachman test evaluated. Quantification of a clinical observation. Clin Orthop Relat Res 1987;216:141-50.
32. Benjaminse A, Gokeler A, van der Schans CP. Clinical diagnosis of an anterior cruciate ligament rupture: A meta-analysis. J Orthop Sports Phys Ther 2006;36:267-88.
33. Vaishya R, Hasija R. Joint hypermobility and anterior cruciate ligament injury. J Orthop Surg 2013;21(2):182-4.
34. Anderson AF, Snyder RB, Federspiel CF, Lipscomb AB. Instrumented evaluation of knee laxity: A comparison of five arthrometers. Am J Sports Med 1992;20:135-40.
35. Rose NE, Gold SM. A comparison of accuracy between clinical examination and magnetic resonance imaging in the diagnosis of meniscal and anterior cruciate ligament tears. Arthroscopy 1996;12:398-405.
36. Taylor JB, Waxman JP, Richter SJ, Shultz SJ. Evaluation of the effectiveness of anterior cruciate ligament injury prevention programme training components: A systematic review and meta-analysis. Br J Sports Med 2015;49:79-87.
37. Yoo JH, Lim BO, Ha M, Lee SW, Oh SJ, Lee YS, *et al.* A meta-analysis of the effect of neuromuscular training on the prevention of the anterior cruciate ligament injury in female athletes. Knee Surg Sports Traumatol Arthrosc 2010;18:824-30.
38. Myer GD, Sugimoto D, Thomas S, Hewett TE. The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: A meta-analysis. Am J Sports Med 2013;41:203-15.
39. Ramski DE, Kanj WW, Franklin CC, Baldwin KD, Ganley TJ. Anterior cruciate ligament tears in children and adolescents: A meta-analysis of nonoperative versus operative treatment. Am J Sports Med 2014;42:2769-76.
40. Samora WP 3rd, Palmer R, Klingele KE. Meniscal pathology associated with acute anterior cruciate ligament tears in patients with open physes. J Pediatr Orthop 2011;31:272-6.
41. Lawrence JT, Argawal N, Ganley TJ. Degeneration of the knee joint in skeletally immature patients with a diagnosis of an anterior cruciate ligament tear: Is there harm in delay of treatment? Am J Sports Med 2011;39:2582-7.
42. Kaeding CC, Aros B, Pedroza A, Pifel E, Amendola A, Andrish JT, *et al.* Allograft versus autograft anterior cruciate ligament reconstruction: Predictors of failure from a MOON prospective longitudinal cohort. Sports Health 2011;3:73-81.
43. Mall NA, Paletta GA. Pediatric ACL injuries: Evaluation and management. Curr Rev Musculoskelet Med 2013;6:132-40.

44. Dekker TJ, Godin JA, Dale KM, Garrett WE, Taylor DC, Riboh JC, *et al*. Return to sport after pediatric anterior cruciate ligament reconstruction and its effect on subsequent anterior cruciate ligament injury. J Bone Joint Surg Am 2017;99:897-904.
45. Beynnon BD, Johnson RJ, Naud S, Fleming BC, Abate JA, Brattbakk B, *et al*. Accelerated versus nonaccelerated rehabilitation after anterior cruciate ligament reconstruction: A prospective, randomized, double-blind investigation evaluating knee joint laxity using roentgen stereophotogrammetric analysis. Am J Sports Med 2011;39:2536-48.
46. Andersson C, Gillquist J. Treatment of acute isolated and combined ruptures of the anterior cruciate ligament. A long term followup study. Am J Sports Med 1992;20:7-12.
47. Andersson C, Odensten M, Gillquist J. Knee function after surgical or nonsurgical treatment of acute rupture of the anterior cruciate ligament: A randomized study with a long term followup period. Clin Orthop Relat Res 1991;264:255-63.
48. Engström B, Gornitzka J, Johansson C, Wredmark T. Knee function after anterior cruciate ligament ruptures treated conservatively. Int Orthop 1993;17:208-13.
49. Cassard X, Cavaignac E, Maubisson L, Bowen M. Anterior cruciate ligament reconstruction in children with a quadrupled semitendinosus graft: Preliminary results with minimum 2 years of followup. J Pediatr Orthop 2014;34:70-7.
50. Longo UG, Ciuffreda M, Casciaro C, Mannering N, Candela V, Salvatore G, *et al*. Anterior cruciate ligament reconstruction in skeletally immature patients: A systematic review. Bone Joint J 2017;99-B: 1053-60.
51. von Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: A study of radiographic and patient relevant outcomes. Ann Rheum Dis 2004;63:269-73.
52. Murray MM, Fleming BC. Use of a bioactive scaffold to stimulate anterior cruciate ligament healing also minimizes posttraumatic osteoarthritis after surgery. Am J Sports Med 2013;41:1762-70.
53. Kiapour AM, Murray MM. Basic science of anterior cruciate ligament injury and repair. Bone Joint Res 2014;3:20-31.
54. Robson AW. VI. Ruptured crucial ligaments and their repair by operation. Ann Surg 1903;37:716-8.
55. O'Donoghue DH. Surgical treatment of fresh injuries to the major ligaments of the knee 1950. Clin Orthop Relat Res 2007;454:23-6.
56. Sandberg R, Balkfors B, Nilsson B, Westlin N. Operative versus nonoperative treatment of recent injuries to the ligaments of the knee. A prospective randomized study. J Bone Joint Surg Am 1987;69:1120-6.
57. Mastrangelo AN, Haus BM, Vavken P, Palmer MP, Machan JT, Murray MM, *et al*. Immature animals have higher cellular density in the healing anterior cruciate ligament than adolescent or adult animals. J Orthop Res 2010;28:1100-6.
58. Nau T, Teuschl A. Regeneration of the anterior cruciate ligament: Current strategies in tissue engineering. World J Orthop 2015;6:127-36.
59. Nohara H, Kanaya F. Biomechanical study of adjacent intervertebral motion after lumbar spinal fusion and flexible stabilization using polyethylene-terephthalate bands. J Spinal Disord Tech 2004;17:215-9.
60. Anderson AF. Transepiphyseal replacement of the anterior cruciate ligament in skeletally immature patients. A preliminary report. Journal of Bone and Joint Surgery. 2003;85-A(7):1255-63.
61. Guzzanti V, Falciglia F, Stanitski CL. Physeal-Sparing Intraarticular Anterior Cruciate Ligament Reconstruction in Preadolescents. American Journal of Sports Medicine. 2003;31(6):949-53.
62. Cordasco FA, Mayer SW, Green DW. All-Inside, All-Epiphyseal Anterior Cruciate Ligament Reconstruction in Skeletally Immature Athletes: Return to Sport, Incidence of Second Surgery, and 2-Year Clinical Outcomes. American Journal of Sports Medicine. 2017;45(4):856-63.
63. Wall EJ, Ghattas PJ, Eismann EA, Myer GD, Carr P. Outcomes and Complications After All-Epiphyseal Anterior Cruciate Ligament Reconstruction in Skeletally Immature Patients. Orthopaedic Journal of Sports Medicine. 2017; 5(3):2325967117693604.
64. Kocher MS, Garg S, Micheli LJ. Physeal sparing reconstruction of the anterior cruciate ligament in skeletally immature prepubescent children and adolescents: surgical technique. Journal of Bone and Joint Surgery. 2006;88:283-93.
65. Bonnard C, Fournier J, Babusiaux D, Planchenault M, Bergerault F, de Courtivron B. Physeal-sparing reconstruction of anterior cruciate ligament tears in children: results of 57 cases using patellar tendon. Journal of Bone and Joint Surgery. 2011;93(4):542-7.
66. Koch PP, Fucentese SF, Blatter SC. Complications after epiphyseal reconstruction of the anterior cruciate ligament in prepubescent children. Knee Surgery, Sports Traumatology, Arthroscopy. 2016;24(9):2736-40.
67. McIntosh AL, Dahm DL, Stuart MJ. Anterior cruciate ligament reconstruction in the skeletally immature patient. Arthroscopy. 2006;22(12):1325-30.
68. Kocher MS, Smith JT, Zoric BJ, Lee B, Micheli LJ. Transphyseal anterior cruciate ligament reconstruction in skeletally immature pubescent adolescents. Journal of Bone and Joint Surgery. 2007;89(12):2632-9.
69. Liddle AD, Imbuldeniya AM, Hunt DM. Transphyseal reconstruction of the anterior cruciate ligament in prepubescent children. Journal of Bone and Joint Surgery. 2008;90(10):1317-22.
70. Courvoisier A, Grimaldi M, Plaweski S. Good surgical outcome of transphyseal ACL reconstruction in skeletally immature patients using four-strand hamstring graft. Knee Surgery, Sports Traumatology Arthroscopy. 2011;19(4):588-91.
71. Kumar S, Ahearne D, Hunt DM. Transphyseal anterior cruciate ligament reconstruction in the skeletally immature: followup to a minimum of sixteen years of age. Journal of Bone and Joint Surgery. 2013;95(1):e1.
72. Schmale GA, Kweon C, Larson RV, Bompadre V. High satisfaction yet decreased activity 4 years after transphyseal ACL reconstruction. Clinical Orthopaedics and Related Research. 2014;472(7):2168-74.
73. Calvo R, Figueroa D, Gili F, Vaisman A, Mocoçain P, Espinosa M, León A, Arellano S. Transphyseal anterior cruciate ligament reconstruction in patients with open physes: 10-year follow-up study. American Journal of Sports Medicine. 2015:43(2):289-94.